Fermi National Accelerator Laboratory

FERMILAB-TM-1860

The Fermilab Upgrade — An Overview

S. Holmes

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

January 1989

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

The Fermilab Upgrade - An Overview

January 9, 1989

Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

Operated by Universities Research Association, Inc.
under Contract with the United States Department of Energy

The Fermilab Upgrade — An Overview

January 9, 1989

Contents

The Fermilab Upgrade — An Overview

1 Summary

This report summarizes an upgrade program for the Fermilab Tevatron. This is designed to maintain and extend its potential for High Energy Physics under the constraints imposed by the US program to build the SSC and in the context of the world's inventory, existing and soon to exist, of particle accelerator facilities. Fundamental to this proposal is the assumption that first rate physics with major discovery potential is an essential ingredient in the pre-SSC era. It is likely that the Upgrade program will also develop unique and important niches in collider and fixed target physics in the period beyond SSC operation.

The Upgrade proceeds in three phases. The first phase is already underway and is designed to increase the luminosity of the proton-antiproton collider to $\sim 1 \times 10^{31} cm^{-2} sec^{-1}$ at 1 TeV $\times$ 1 TeV. It will also increase the fixed target intensity to $\sim 3 \times 10^{13}$ ppp (from the present 1.5×10^{13} ppp) and provide a modest increase in energy to 900 GeV.

In the second phase the present Main Ring is replaced with a new Main Injector in a separate subsurface enclosure. Initial (peak) luminosity in collider physics is then expected to increase to $\sim 2.5 \times 10^{31} cm^{-2} sec^{-1}$. The Main Injector would be capable of delivering $\sim 6 \times 10^{13}$ protons to the Tevatron. This machine will have a high repetition rate and, in addition to its use as a $\bar{p}$ producer and source of test and calibration beams for fixed target users during collider operation, its high repetition rate will provide a unique source of 120 GeV protons for high energy physics. It is proposed to initiate the R&D phase in FY90, the construction in FY91, with completion scheduled for 1995.

In the last phase a second superconducting synchrotron is installed in the collider tunnel. Collider physics will be carried out at an energy of 1.8 TeV per beam and at a luminosity of $\sim 4 \times 10^{31} cm^{-2} sec^{-1}$. The enhanced physics potential resulting from this phase arises from the energy increase rather than from the relatively modest luminosity increase. Fixed target physics will be carried out at an energy of 1.5 TeV, the lower energy being necessitated by cryogenic considerations. High field magnet R&D is currently in progress at a modest level. It is proposed to enlarge this R&D program in FY90 pointing toward a start of the construction project in FY92. Project completion is scheduled in FY95 so that installation of both the Main Injector and the New Tevatron can take place during a single shutdown period. This will be the only substantial shutdown (9 - 11 months) in the Upgrade plan.

In the body of the report a lengthy section is devoted to the physics motivations associated with this upgrade. Following that section, the various stages are treated briefly. Because of the long lead time associated with the high field magnet R&D program and the substantial cost of the New Tevatron, this phase is discussed first, followed by the Main Injector. The present phase is discussed last; to a large extent, it is already underway. Cost tables are provided in the last section.

1.1 Context, Constraints, and Conclusions

The Fermilab Upgrade plan has profited from wide discussion in the HEP community and in particular with URA, DOE, HEPAP, and the Fermilab Users Group. It has been assumed, with considerable enthusiasm, that the SSC will indeed come on and begin to publish physics results by 1998. This is a prudent assumption for the community to accept. If LHC indeed becomes a European project, there is no way that, as presently described by Carlo Rubbia, it can substantially beat SSC. LEPI should become operational by 9:00 a.m. of July 14, 1989 and LEPII about 2-3 years later. HERA, at $\sqrt{s} = 330$ GeV wil begin to commision in 1990. UNK is harder to estimate but the best guess is that the 3×3 TeV phase will come late in the 1990's. Recall that neither UNK nor LHC have begun the 7-10 year task of constructing a high luminosity 4π detector. All this is to assert that the Tevatron at $\sqrt{s} \geq 2$ TeV will be the highest energy, fully commissioned and instrumented accelerator for the next decade. This makes it eminently logical that Fermilab and the US community exploit this feature and this inevitably implies the Upgrade program. *To sharpen this, there is already reasonably solid evidence from early CDF results that new physics will very likely require at least* $100pb^{-1}$ *of integrated luminosity.*

In planning the Upgrade, other factors entered the decision making. These had to do with the fact of SSC, its timing and its impact on funding and on people, the latter coming in two flavors, accelerator and user types. Thus, for example, the construction of a new general purpose 4π detector that could survive at $\sim 10^{32} cm^{-2} sec^{-1}$ was ruled out.

A detailed study of user demographics indicates that the Upgrade program is compatible with a decrease in Fermilab user population by 300-400 from the peak of 1300. With proportional flow from other HEP activities and a large foreign contingent, SSC should have no trouble with its user population. The problem of accelerator physicists is somewhat harder but there exists a vast population of non-HEP accelerator experts. (Witness the accelerator conferences where HEP people constitute only 20% of the attendees.)

The financial constraints assumed an HEP budget of \$560 million in 1989 dollars. Out of this, considering the sums conventionally spent on construction, over \$50 million per year (i.e., 10% of SSC) is affordable for non-SSC HEP construction. The Upgrade requires an average of about \$50 million in FY89 dollars in the years 1990-1995. New non-SSC ventures can begin in 1995-6 and may perhaps even proceed with increasing vigor as SSC funding begins to decrease. No large requirement for associated operating increases is forseen since the Upgrade is essentially a series of replacements.

The need to keep shutdowns short and to keep the machine on for physics has been emphasized. Thus the only significant (9-11 months) shutdown planned will be in 1995 for the installation of Phase III and the concurrent attachment of the new Main Injector.

The Upgrade plan also considers life beyond the SSC. There will be niches that will provide complementary physics just as the AGS is now providing with rare K decays. Although it is too early to predict, the Main Injector is seen as a unique instrument for difficult experiments involving very intense and fairly energetic kaons and neutrino beams. Also the collider, when not pushing on high energy, can provide three or more interaction regions for a variety of very specialized kinds of physics, e.g., B physics if SSC backgrounds prove to be terrible, structure functions at $x \sim 10^{-4}$, detailed studies of jet structures, etc. The future of the "standard" fixed target program in the SSC era will depend on the success of UNK's 3 TeV machine.

A crucial element in the Upgrade is the fact that CDF (and soon D0) is confronting formidable problems in high rate, low cross-section hadron physics. With the Upgrade they will be confronting subtle signatures at the level of 10^{-11} to 10^{-12} of the total cross-section. *There is no way of simulating this experience.* The Upgrade, in addition to the impressive physics potential, is guaranteed to provide unique experience in this crucial area. Prospects for successful exploitation of the Upgrade seem excellent. There is no sign that CDF is running into detector limitations. Extremely clean dijets have been recorded at a rate of about 100 events per pb^{-1} above a mass of 300 GeV/c^2. Thus, the Upgrade will yield tens of thousands of hard collision events on the constituent level at energies well beyond LEPII and HERA.

Progress in the understanding of physics, progress in detector technology with the detector upgrades, progress in accelerator technology as increasingly denser bunches are handled, and progress in the training of physicists are all essential ingredients in a successful exploitation of the SSC. As everyone knows, the stakes are much bigger in Texas!

In summary, a proposal is presented here that, admittedly, will put some stress on the community in the SSC construction era but which is in fact responsible, affordable with *absolutely unique* capabilities for learning new physics and essential techniques. This plan is believed to be correct primarily because it offers the best physics potential within the constraints imposed.

2 Introduction

2.1 Brief Description

For at least the next decade, the Tevatron will remain the focus of the US High Energy Physics Program. The Tevatron is not without competition in its ability to advance the frontiers of elementary particle physics. Even today the Sp$\bar{p}$S is a serious competitor because of its higher luminosity in spite of its lower energy. For the Tevatron to be able to maintain its status as the pre-eminent high energy facility it must be improved to fully exploit its potential during this time span. This report describes a three phase upgrade program which can provide opportunities at the forefront of physics in both the fixed target and colliding beams physics activities at Fermilab in the pre-SSC era. The lessons of history are also clear in that, with the Upgrade, it is likely that areas of physics will exist for which the Tevatron may be more appropriate than the SSC, given the importance of the highest energy, especially in the early years of SSC physics.

Collider physics, when done with a slowly evolving general purpose 4π detector at a fixed energy, demands something like a doubling of the integrated luminosity with each run in order to maintain the discovery potential for new physics at each stage. The Tevatron I project set 10^{30} cm^{-2} sec^{-1} as the design luminosity, and that has been achieved and exceeded. The new program calls for increasing the luminosity from run to run until a peak of a few $\times 10^{31}$ cm^{-2} sec^{-1} is achieved and integrated luminosities per run in excess of $100pb^{-1}$ are feasible. Indeed, data from the 1988/89 CDF run, tentative as they are, indicate that runs of the order of $100pb^{-1}$ will be essential for new physics. In this upgrade plan it is proposed finally to both double the energy and the luminosity in order to extend the physics reach to the ultimate capability of the existing Main Accelerator enclosure. Fixed target experiments will also benefit from the increases in both proton energy and intensity.

The Upgrade proceeds through three phases, the first of which is already underway. In this initial phase, improvements to the antiproton source, the installation of separators in the Tevatron, new interaction region optics for the two major detectors, and the increase in the linac energy to 400 Mev will bring the luminosity to the 10^{31} cm^{-2} sec^{-1} level for the fourth collider run in 1992. Cryogenic system modifications should permit operation of the Tevatron at 1 TeV for collider physics, and 900 GeV for fixed target physics. The projected total cost of this phase in then year dollars (1989-1991) is \$48.3 million of which the linac upgrade is a major component.

The second phase consists of a significant construction project: the replacement of the Main Ring with a Main Injector in a separate subsurface enclosure. Collider runs subsequent to its commissioning are expected to enjoy another step of about a factor of 2.5 in luminosity, and there are a variety of other benefits as well, including an increase of the fixed target intensity to above pre-Tevatron levels, the removal of a major background source from the colliding beam interaction regions, and provision of a new and unique source of extremely intense beams of 120 GeV protons.

In the third and final phase, the space in the collider tunnel vacated by the Main Ring is to be occupied by a second superconducting synchrotron. The high field magnets of this new ring are designed for operation at 6.6 Tesla at a temperature of 4.2 K, corresponding to an energy of 1.5 TeV. By cooling the ring to 1.8 K, the energy would be increased to 1.8 TeV. The energy enhancement would in addition increase the luminosity for proton-antiproton collisions to $4 \times 10^{31}\ cm^{-2}\ sec^{-1}$.

The first phase, except for the linac, will be completed in 1991. The completion date of the linac, if funded in 1990, would be in 1992. The required shutdown for installation is measured in weeks. The Main Injector, if funded in 1991, could be in operation in 1995. The New Tevatron, if funded in 1992, could be ready at the same time.

The total cost of the three phases can be funded with an increment of about $50 million a year to the Laboratory's base budget, in 1989 dollars. It is also a sensible investment which will buy exciting discovery potential, solid advance of our knowledge base, and invaluable experience in handling high luminosity collisions. All of this will serve to make SSC more efficient, which in itself has an enormous pay-back ratio. Of course, it is expected that shortages of funds and people will be an important new environmental issue in non-SSC HEP. This has been used as a constraint. Other constraints had to do with minimizing the downtime of the Tevatron and understanding fully the importance of both the collider and fixed target programs proceeding with full steam during the Upgrade program.

The remainder of this introduction comments on the options that were considered before Fermilab chose the particular sequence of improvements described here, and on the implications of that sequence for parameter choices. In the course of making these choices, wide ranging discussions and presentations were held in the high energy community.

Subsequent sections of this document discuss the physics capability of the various phases, a brief description of each phase, and an estimated cost of the additional funding that Fermilab would need to carry out the design and construction of the major additions to the accelerator capabilities; the 400 MeV linac, the Main Injector, and the New Tevatron. It is assumed that the cost of upgrading detectors and the other smaller additions to the accelerator–switchyard complex are done within the framework of the existing Fermilab budget, i.e., the requested FY90 budget.

2.2 Selection from Variety of Options

The program presented represents the distillate of several years of planning and of weighing the alternatives. To suggest the extent of this process, the two other upgrade paths that were explored in detail are mentioned here. The first phase remains the same in all of the plans; it is only the later stages that differ.

A year ago, a design report was prepared for a somewhat higher luminosity, but technically more challenging approach to proton-antiproton collider physics. Two 20 GeV synchrotrons were at its heart. One was to be a second booster synchrotron to receive 8 GeV beam from the existing booster and deliver its output to the Main Ring at 20 GeV. Low field and transition crossing problems in the Main Ring would thereby be avoided. The second ring was to be a storage device for antiprotons, received either from the existing accumulator, or from the Tevatron via the Main Ring to be recooled. Although the goal of the study was to establish a design capable of a luminosity of $5 \times 10^{31} cm^{-2} sec^{-1}$, the technological difficulty of the plan that emerged made $2 \times 10^{31} cm^{-2} sec^{-1}$ appear to be a more realistic limit.

These concerns for the difficulties of achieving the desired performance as well as the limited growth potential led to a design study on a 1 TeV on 1 TeV proton-proton collider. In order to provide the space for two superconducting synchrotrons in the Main Accelerator enclosure, the Main Ring was removed from this enclosure and its role taken over by a separate 150 GeV Main Injector in its own enclosure. A second 1 TeV superconducting synchrotron would be installed to make possible proton-proton collisions at a luminosity well in excess of $10^{32}\ cm^{-2}\ sec^{-1}$. While this plan offered advantages for certain areas of physics, it required entirely new detectors. Because the construction of these new detectors would have to use the facilities of the existing assembly halls for CDF and D0, a massive disruption of the ongoing program appeared inevitable. Then too, the required number of users and funds could exceed the imposed constraints. This plan did provide some benefits to the fixed target program because the Main Injector was a much superior machine to the present Main Ring.

The Upgrade as outlined here combines the continued concentration on single-ring collider physics of the first plan with the exploitation of a second superconducting ring as in the second, to provide a program that extends the discovery reach of the Fermilab facility through a combination of luminosity and energy increase. The Upgrade has the advantage that the detector improvements required to keep pace with the gradually increasing Tevatron luminosity can be made adiabatically during the times allocated to fixed target operation. Moreover, the cost of these improvements (see Sec. 7) is far less than the cost of entirely new detectors. The discovery reach of the collider experiments in this plan is on balance superior to the other two. Finally, the New Tevatron nearly doubles the energies of the fixed target beams, and the Main Injector creates a unique new facility which makes it possible to exploit the intense good duty factor beams of 120 GeV protons for physics and detector development during collider operation.

2.3 Criteria and Technical Constraints

The aim of the next few paragraphs is to show how the luminosity and energy goals above turn into parameter choices, and, especially, to highlight the importance of antiproton stack size, antiproton stacking rate, and separated beams.

The luminosity for head-on collisions may be written

$$\mathcal{L} = \frac{3}{2}\gamma f_o \frac{B N_p N_{\bar{p}}}{\epsilon_N \beta^*}$$

where B is the number of bunches in each beam, the N's are the number of particles in each bunch for the two particle species, f_o is the revolution frequency of the synchrotron, β^* is the amplitude function in both transverse degrees of freedom at the interaction point, γ is the Lorentz factor, and ϵ_N is the normalized emittance. The factor of 3/2 is associated with the specific definition of emittance — i.e., the phase space area containing 95% of a gaussian beam — but is not particularly relevant because the emphasis will be on scaling arguments.

The original antiproton collider design report specified a luminosity of $10^{30}\ cm^{-2}\ sec^{-1}$ through the collision of three proton bunches with three antiproton bunches, each containing 6×10^{10} particles with a normalized emittance of $24\pi\ mm\ mrad$ at an interaction point where $\beta^* = 1\ m$. Shorn of powers of ten and other constants, the luminosity expression for the design has the pattern

$$\mathcal{L} \propto \frac{BN_pN_{\bar{p}}}{\epsilon_N\beta^*} = \frac{3\times6\times6}{24\times1}.$$

A combination of circumstances— particularly an antiproton production cross section lower than that assumed in the design and the restricted transverse admittance of the Main Ring — resulted in the use of the pattern

$$\frac{6\times6\times2}{24\times2/3}$$

to obtain the design luminosity. As this is written, the typical initial luminosity of a store is $1.5\times10^{30}\ cm^{-2}\ sec^{-1}$, with the pattern

$$\frac{6\times7\times2}{24\times1/2}$$

It is from this situation that the Upgrade begins.

The denominator of the luminosity expression offers relatively little flexibility for major gains. If the amplitude function at the interaction point is reduced significantly below 0.5 m, the bunch length correction diminishes the potential benefits of low β^*. Though the new interaction region optics permit $\beta^* = 1/4$ m, no value lower than 0.5 m will be used in the following discussion. A potential change in frequency of the acceleration system is held in reserve as a means of escaping this limitation.

The other factor in the denominator is the emittance. Quite aside from the difficulty of producing and maintaining beams of arbitrarily small emittances with reasonable intensity, there is a limitation due to the beam-beam effect, and that couples the emittance with one of the bunch intensities in the numerator. The proton bunch intensity is at least as large as the antiproton bunch intensity throughout the Upgrade, and so the former intensity will be used. The betatron oscillation tune spread experienced by the antiprotons is approximately

$$\begin{aligned}\Delta\nu &= H\cdot\frac{3N_pr_o}{2\epsilon_N}\\ &= 0.0075H\frac{N_p\times10^{-10}}{\epsilon_N\times10^6/\pi}\end{aligned}$$

where H is the number of passages through oncoming bunches per turn and r_o is the classical radius of the proton. The necessity of avoiding low-order resonances limits the tune spread to a value of about 0.02. At present, the collider operation is tune spread limited , with $\Delta\nu\approx0.025$. The emittance of the protons is intentionally increased by almost a factor of two before injection of the antiprotons to keep the tune spread within bounds. By separating the proton and antiproton orbits except at the collision points, H can be reduced from 12 to

2, the lower limit corresponding to the number of major detectors that will be in operation for the next collider run. The present separator scheme allows for 44 bunches of each particle type. Nearly a factor of 2 in luminosity can then be gained as it will no longer be necessary to dilute the particle emittances. But to reach the goal of $2.5 \times 10^{31} cm^{-2} sec^{-1}$ at 1 TeV$\times$1 TeV another factor of 10 must be found.

The remaining factors in the luminosity expression, $BN_{\bar{p}}$, represent the total number of antiprotons in the collider. In order to capitalize further on the avenue to higher luminosity provided by separated beams, it is necessary to improve both the antiproton stack size and the stacking rate. The stack size must, of course, be larger than the number of antiprotons required to fill the collider. The overall transfer efficiency from accumulator stack to low-β collisions is now about 70% to 80%, and so 12×10^{10} antiprotons undergoing collision implies the extraction of about 17×10^{10} from the accumulator. This in turn requires a stack size of about 30×10^{10} antiproton Though the number of extracted antiprotons will go up by an order of magnitude, it is a cipated that the required stack need only be about 25% larger than the number extracted, as a result of increasing the number of bunches.

The storage time is likely to remain roughly constant. In today's operation, the luminosity lifetime is sufficient to permit stores in excess of a day, but the actual average store duration is just under 14 hours. Most stores are terminated unintentionally due to a variety of fault conditions. While the sources of these fault conditions will be gradually eliminated, the new equipment associated with the Upgrade will inevitably bring new causes for store termination. Therefore, it is planned to improve the stacking rate by nearly an order of magnitude throughout the Upgrade.

The progression in luminosity, stack size, and stacking rate is summarized in Table 1. To reach these design luminosities, only 22 bunches are needed, consistent with the projected capabilities of the antiproton source during the Upgrade. Should the source be able to produce larger stacks, it is conceivable that the luminosity could go up by as much as another factor of two.

Phase	$\mathcal{L}$	$\frac{BN_{p}N_{\bar{p}}}{\epsilon_N \beta^*}$	Δ_{Stack}	p/sec	$\bar{p}/p$	Rate($\bar{p}/hr$)	$\frac{\Delta_{Stack}}{Rate}$
Now	1.5×10^{30}	$\frac{6\times7\times2}{24\times1/2}$	17×10^{10}	0.65×10^{12}	7×10^{-6}	1.7×10^{10}	10
Ia	7×10^{30}	$\frac{6\times6\times5}{12\times1/2}$	43×10^{10}	0.85×10^{12}	10×10^{-6}	3.1×10^{10}	14
Ib	1×10^{31}	$\frac{22\times6\times2}{12\times1/2}$	64×10^{10}	1.4×10^{12}	14×10^{-6}	7.0×10^{10}	9
II	2.5×10^{31}	$\frac{22\times6\times5}{12\times1/2}$	13×10^{11}	2.8×10^{12}	14×10^{-6}	14×10^{10}	9
III	4×10^{31}	$\frac{22\times6\times5}{12\times1/2}$	13×10^{11}	2.8×10^{12}	14×10^{-6}	14×10^{10}	9

Table 1: Progress in initial luminosity, stack size, and stacking rate throughout the Upgrade. The initial phase is divided into two parts; Ia is everything except the 400 MeV linac and the antiproton target sweeping system, and Ib includes the linac. The luminosity pattern is the same as that used in the text.

3 Physics Motivation

There are at least 19 basic parameters of the Standard Model. The Collider and Fixed Target Upgrade program addresses issues as fundamental as these parameters:

1. Gauge Couplings: Precision measurements of the electroweak coupling α_w (or equivalently $sin^2\theta_w$) come both from the Collider program through measurements of the properties of the $W^\pm$ and Z^0 and from the neutrino program.

   The 'running' of α_s is proposed to be well-measured for the first time via a future muon scattering experiment.

2. Masses: If not already found with the present Tevatron, the top quark mass should be determined, or at least tightly constrained, with the Upgrade. Fourth generation (or other) quarks and leptons are also objects of search in the Collider program. The Main Injector provides a powerful tool for searching for neutrino masses and mixings.

3. Mixings: Two of the four independent KM parameters need determination. The unitarity of the KM matrix should be tested. Both the Fixed Target and Collider programs directly address these questions.

4. Higgs Sector: While the standard Higgs particle seems out of reach, variants (axions, charged Higgs', technicolor, ...) need not be. Considerable discovery potential exists for these variants.

In addition, there exists in the program considerable sensitivity to phenomena beyond the Standard Model, not only in the Collider mode but also in the Fixed Target program (e.g. experiments on rare K decays using beams from the Main Injector).

Clearly this program addresses extremely basic issues. In what follows the physics potential of the Upgrade program is presented in more detail.

The Phase I (a and b) Upgrade will increase the luminosity for $\bar{p}p$ collisions to a peak luminosity of $\mathcal{L} = 10^{31}cm^{-2}sec^{-1}$ and raise the energy of collisions to $\sqrt{s} = 2.0$ TeV. This will provide a substantial increase from the present peak luminosity of approximately $\mathcal{L} = 1.5 \times 10^{30}cm^{-2}sec^{-1}$ along with a modest increase in energy from the present 1.8 TeV. Phase Ia includes all of the improvements that have been underway since 1987, to make it possible to provide CDF and D0 with simultaneous high luminosity interaction regions. The commissioning of the D0 detector will be concurrent with the completion of Phase Ia. Phase Ib corresponds to an upgrade of the existing 200 MeV linac to a 400 MeV linac. The improvement will increase both the rate at which antiprotons are accumulated and the quality of the proton beams.

Phase II involves the construction of a Main Injector in a separate tunnel. This will improve the luminosity for $\bar{p}p$ collisions by another factor of 2.5 and remove a major source of background from the colliding beam interaction regions. It will also increase the proton intensities for fixed target running by at least a factor of three. This will be particularly important for the fixed target heavy quark physics program. It will be possible to transport 120 GeV protons from the Main Injector to all targets in the fixed-target experimental areas during Collider operation of the Tevatron. The primary and secondary beams can be used to check out the large multiparticle spectrometers prior to the changeover of the Tevatron to fixed-target operation. This will significantly reduce the two months of Tevatron time now being used for detector startup thereby making better use of the Tevatron fixed-target beam time. The very high intensity source of protons from the Main Injector will create unique opportunities for neutral kaon physics and neutrino physics. These fixed target physics opportunities are a natural extension of work in progress at Fermilab and will be discussed below in subsequent sections. It will make test beams available for SSC detector development and Tevatron collider detector calibration throughout most of the year. Finally, but not the least of the benefits, it permits the possibility of creating a third interaction region for high luminosity collider physics. Such a region would open the way for the Bottom Collider Detector (BCD) proposal, now in the process of being formulated.

In Phase III a New Tevatron will be installed in the present tunnel. This new ring will increase the energy for $\bar{p}p$ collisions to $\sqrt{s} = 3.6$ TeV. Furthermore, the peak luminosity will increase to $\mathcal{L} = 4 \times 10^{31} cm^{-2} sec^{-1}$.

The Upgrade will enrich both the collider and fixed target programs at Fermilab. However, since the major thrust of the Upgrade program is to improve the physics potential for the Collider program a detailed exposition of the physics benefits is given here. In order to present such a quantitative discussion of the physics motivation a number of parameters and assumptions need definition.

The experience of the past three years of operating the Tevatron for collider physics and fixed target physics indicates that a standard collider run will have a duration of ten months. Eight of these months will be scheduled for high luminosity collider physics at B0 (CDF) and D0. The other two months will be used for special runs, the times when low luminosity experiments at E0 and C0 will be scheduled, and accelerator studies. The record shows that 4×10^5 seconds ($\sim$110 hours) of stored beam can be achieved reliably during a week. The average luminosity during a store is typically 45% of the initial luminosity. Hence, a standard run will be equivalent to $\sim 6 \times 10^6$ seconds at peak luminosity. Another factor must be included to take into account the detector efficiency. Presently, the Tevatron Collider operates at a center of mass energy ($\sqrt{s}$) of 1.8 TeV and an initial luminosity which averages $\mathcal{L} = 1.5 \times 10^{30} cm^{-2} sec^{-1}$. To date, an integrated luminosity of $4 pb^{-1}$ has been delivered to CDF and $1.5 pb^{-1}$ has been recorded on tape. A suitable goal for this run is a total integrated luminosity of $5 pb^{-1}$ on tape. For the remainder of the run it would thus be necessary to deliver approximately $6.5 pb^{-1}$ to CDF with $3.5 pb^{-1}$ recorded on tape, consistent with recent detector efficiency.

In future runs, the detector efficiency is expected to reach 80% routinely. An extrapolation of the performance to date indicates that with the completion of Phase II of the Upgrade a standard run at center of mass energy of 2 TeV and peak luminosity of $2.5 \times 10^{31} cm^{-2} sec^{-1}$ will yield $100 pb^{-1}$. At the completion of Phase III, with center of mass energy of 3.6 TeV and peak luminosity of $4 \times 10^{31} cm^{-2} sec^{-1}$, the yield, at this higher energy, for a standard run would be $200 pb^{-1}$ within the uncertainties of these estimates.

To study the physics potential of this proposed Upgrade it is useful to consider its various phases as well as a potential pp option:

1. Phase II - The Upgrade after the completion of the Main Injector. Although the energy for $\bar{p}p$ collisions will remain at $\sqrt{s} = 2.0$ TeV, the Main Injector will increase the peak luminosity by a factor of 2.5, from $\mathcal{L} = 1.0 \times 10^{31} cm^{-2} sec^{-1}$ at the end of Phase I to $\mathcal{L} = 2.5 \times 10^{31} cm^{-2} sec^{-1}$. Thus a standard run would yield an integrated luminosity of $100 pb^{-1}$.

2. Phase III - The proposed New Tevatron at its maximum energy $\sqrt{s} = 3.6$ TeV. With a peak luminosity $\mathcal{L} = 4 \times 10^{31} cm^{-2} sec^{-1}$ a standard run would yield an integrated luminosity of $200 pb^{-1}$. For many reactions this extra energy is equivalent to a <u>much</u> higher (3 to 5) luminosity at 2.0 TeV. This can be read from the graphs or Table IV below.

3. pp Option – A second ring in the Tevatron tunnel allows the possibility of pp collisions at an energy of $\sqrt{s} = 2.0$ TeV but with a higher peak luminosity $\mathcal{L} = 2 \times 10^{32} cm^{-2} sec^{-1}$. For this option, a standard run could produce an integrated luminosity of at least $1000 pb^{-1}$. This option is left as a distant one, for both CDF and D0 are probably not upgradable to these luminosities.

The physics potential of the Tevatron Collider program can be divided into three broad classes: Standard Model Physics, Minimal Extensions, and New Directions. Each of these classes will be discussed in turn. After a summary of the Collider physics motivations, there is a brief discussion of the benefit to the fixed target program of the higher energy of the New Tevatron. New physics opportunities associated with the Main Injector are discussed in the final section.

3.1 Standard Model Physics

At the Tevatron the physics of the standard model can be studied in great detail. Perhaps the most exciting opportunity at present is the discovery and subsequent study of the top quark in $\bar{p}p$ collisions. The lower bound on the top mass is 41 GeV/c^2 which comes from the analysis of UA1 data. [1] There are no reliable theoretical predictions for the top mass. However within the Standard model with three generations there is an upper bound on the possible top mass which is determined by the deviation of the ρ parameter from unity. [2] The present experimental constraints on the ρ parameter imply that top is no heaver than 180 GeV/c^2. At Tevatron energies and above the dominant mechanism for producing top (or any heavy quark) is gluon fusion. The cross section for heavy quark production via gluon fusion is shown in Figure 1 for the present Tevatron energy, the various Upgrade phases, and the pp Option. The detection of a top signature may require as few as 100 produced pairs, while a clear proof of top accompanied with a mass measurement will require as least 1000 produced pairs. Therefore with $5 pb^{-1}$ CDF can measure the top mass up to 80 GeV/c^2 and see evidence for top for masses up to 120 GeV/c^2. The Upgrade will extend the range for an

[1] G. Altarelli et. al., Nucl. Phys. B308, 724 (1988).

[2] P. Langacker, W. M. Marciano, and A. Sirlin, Phy. Rev. D36, 2191 (1987). Also see U. Amaldi et. al, Phy. Rev. D36, 1385 (1987).

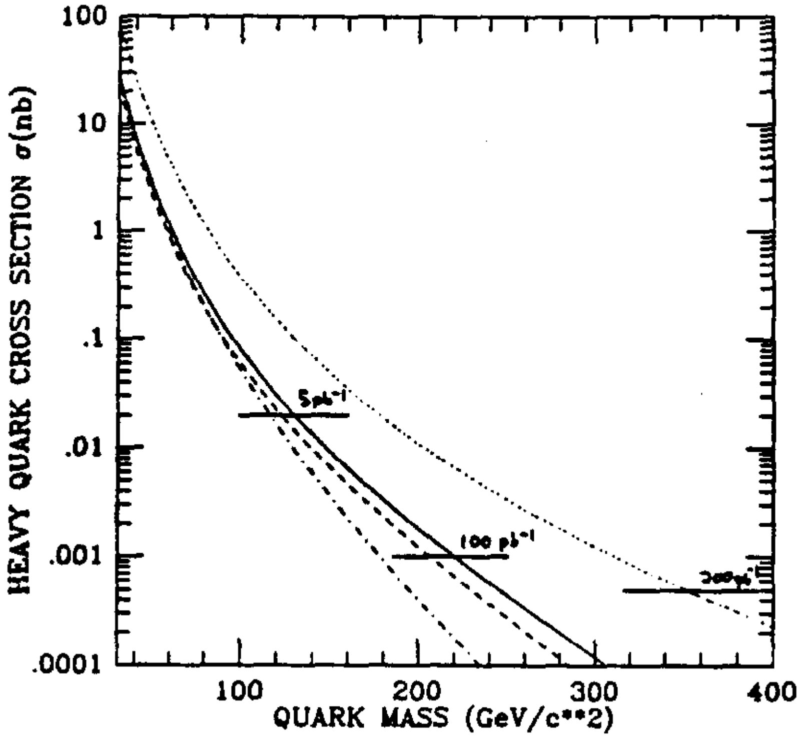

Figure 1:
Total cross section, σ(nanobarns), for pair production of heavy quarks (by gluon fusion) in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV (dashed curve), 2.0 TeV (solid curve), and 3.6 TeV (dotted curve): and in pp collisions at $\sqrt{s} = 2.0$ TeV (dash-dotted curve). The EHLQ parton distribution functions (with $\Lambda = 290$ MeV) were used. The cross sections required to produce 100 heavy quark pairs in a standard run of integrated luminosity of $5pb^{-1}$, $100pb^{-1}$, and $200pb^{-1}$ are indicated by horizontal solid lines. The cross section required with an integrated luminosity of $1000pb^{-1}$ is $.1pb$.

Table 2: Event Rates For Standard Particles

Particle (Mass)	Events in Standard Run			
	Now	PhaseII	Phase III	pp Option
$b(4.75GeV/c^2)$	2.5×10^8	5.5×10^9	2.0×10^{10}	5.5×10^{10}
$W^\pm(81GeV/c^2)$	6×10^4	1.3×10^6	3.6×10^6	7.5×10^6
$Z^0(92GeV/c^2)$	2.0×10^4	4.4×10^5	1.3×10^6	3.0×10^6
$W^\pm\gamma(E_T^\gamma > 10GeV)$	75	1640	5800	6300
W^+W^-	32	750	2400	3000
$W^\pm Z^0$	8	180	640	880
Z^0Z^0	4	90	360	370

accurate mass measurement to 230 GeV/c^2. Since this is safely above the theoretical upper bound on the top mass, the discovery of top within the Standard Model will be assured with the Upgrade. In the more fortunate circumstance that top will be discovered at a much lower mass, perhaps even in the present collider run, the New Tevatron will allow Fermilab to become a top factory. For example, if the top mass is 80 GeV/c^2 then in the present run approximately 1250 top pairs would be produced, while in a standard run 220,000 top pairs would be produced with the New Tevatron (as compared to 25K for Phase II and 200K for pp Option). These rates allow the potential for studying possible rare decay modes or a significant nonstandard decay mode, eg. charged Higgs ($H^+ + b$) or fourth generation leptons ($L^+ + \nu_L + b$).

The collider will also produce sufficient events to allow detailed studies of the electroweak bosons ($W^\pm$ and Z^0) and the bottom quark. Table 2 shows the number of produced events for various known particles at the present Tevatron with integrated luminosity of $5pb^{-1}$ as well as standard runs for Phase II and III of the Upgrade and a standard run for the pp Option. While the full upgrade is slightly inferior to the pp Option in each of these measures of standard particle production, the benefit of the pp option can only be realized by replacing both the CDF and D0 detectors. Moreover, the increase in new physics potential with the proposed Upgrade program is greater than the pp option.

The study of bottom meson decays, mixing, and CP violation will provide critical information about the quark mixing matrix (i.e. the KM matrix) in the three generation standard model. It is very likely that most of the information about B_u and B_d mesons obtained in the next 5 years will come from LEP and CESR and a smaller but significant contribution from the Fermilab fixed-target program. In particular, with a planned upgrade CESR will be capable of producing 10^7 B mesons per year by 1995. Some exploration of the physics of B_s mesons and b quark baryons will likely occur at Fermilab.

There are still large uncertainties in the total hadronic rate of bottom quark production. Recently, the full calculation through order α_s^3 has been completed. [3] The results are shown in Figure 2. The range of theoretical uncertainty is indicated by the upper (dotted) and

[3] P. Nason, S. Dawson, and R. K. Ellis, Nucl. Phys. B303, 607 (1988).

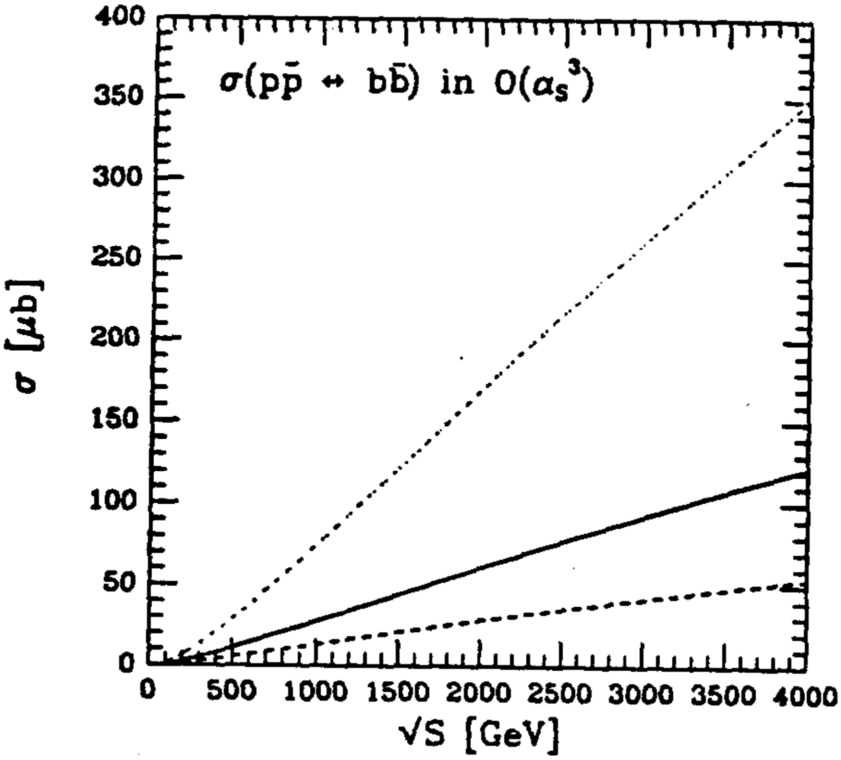

Figure 2:
Total cross section, σ(nanobarns), in order α_s^3 for the production of the bottom quark via gluon fusion in $\bar{p}p$ as a function of center of mass energy $\sqrt{s}$ (GeV). The theoretical uncertainties are illustrated by three choices of the three parameters of the calculation: The bottom quark mass, m; the QCD scale, Λ; and the scale of the process, μ. The middle (solid curve) uses the nominal values of these parameters: $m = 4.75$ GeV, $\Lambda = 170$ MeV, and $\mu = m$. The largest cross section (dotted curve) uses extreme values: $m = 4.5$ GeV, $\Lambda = 250$ MeV, and $\mu = m/2$. The smallest cross section (dashed curve) uses the opposite extreme values: $m = 5.0$ GeV, $\Lambda = 100$ MeV, and $\mu = 2m$. The DFLM parton distribution functions were used.

lower (dashed) curves. Although the variations are large, the dependence of the total cross section with $\sqrt{s}$ is quite accurately linear in the energy range above $\sqrt{s} = 500\mathrm{GeV}$ and hence the ratios of cross sections for the present Tevatron and the Upgrade options should be quite reliable. These ratios are 1.0 to 1.1 to 2.0 to 1.1 for the Tevatron Upgrade Phase II, Upgrade Phase III, and pp Option respectively. The rate of bottom quark production shown in Table 2 is the nominal result of the order α_s^3 calculations. However, as seen from Figure 2 and Table 2, even taking these uncertainties into account the cross section of b quark production would be at least 50 μ b.

In contrast the e^+e^- cross section for $\bar{B}B$ production at the upsilon $(4S)$ is about 1 nb, 10^5 times smaller than the estimated 110 μb cross section for $\bar{B}B$ production in $\bar{p}p$ collisions at 3.6 TeV. Even with the proposed luminosity upgrade of the CESR collider, the New Tevatron will be capable of producing a thousand times more events. In addition the Tevatron provides a Lorentz boost to the $B's$ which gives promise of reconstructing the secondary vertex of the B meson. If the detection problem for $B's$ produced in a hadron collider can be solved as it was solved for charm in fixed-target hadron experiments then the future of b physics could be very bright for the Tevatron. The study of CP violation in the neutral B system would greatly extend the understanding gained from the the K system, leading to a precise determination of all the KM matrix elements. Furthermore, the study of not one or two but many CP-violating decay modes in the B system, would overconstrain these parameters.

The determination of the CP-violating asymmetry of B-decay branching ratios, $A = [\Gamma(B \rightarrow f) - \Gamma(\overline{B} \rightarrow \overline{f})]/[\Gamma(B \rightarrow f) + \Gamma(\overline{B}) \rightarrow \overline{f})]$ directly measures elements of the KM matrix. Such asymmetries are expected to be in the range 0.05-0.30 for some favorable modes. However, it is anticipated that decay modes with large asymmetries have small branching ratios. When the final state f is a CP eigenstate the theoretical interpretation of A is particularly clean. However a very large sample of produced B's is required to make a measurement of this asymmetry. Also, when the final-state $f = \bar{f}$, the identification of the parent B as a particle or an antiparticle must come from a tag based on the reconstruction of the other B in the event. [4]

In order to realize the full potential of the B system, a sample of several thousand B-$\bar{\mathrm{B}}$ events in the modes of interest (branching ratios $< 10^{-5}$) must be fully analyzed, including full reconstruction of one B meson and sufficient reconstruction to identify the particle-antiparticle nature of the other. It is generally accepted that hadron colliders at high energy are the ultimate B factories. This is because of the very large B cross sections, about a millibarn, and the very favorable ratio of the B cross section to the total cross section (about 1%, like charm photoproduction).

The kinematics of B production at the New Tevatron collider are very similar to those at the SSC. Therefore, the technical challenges in mounting an experiment in the collider are similar to the challenges in the low-luminosity (beauty) region at the SSC. Since the challenge is so great, many physicists believe that an intense effort to build such a detector

[4] For a discussion of CP violating decays in the B system, see: F. Gilman, *B Physics*, Proceedings of the Workshop on High Sensitivity Beauty Physics at Fermilab (Nov. 11 - 14, 1987), p. 1 and the references therein.

should begin immediately. Some components could be built after a few years' R&D, others will require many years. But the goal of a major physics measurement prior to the SSC greatly sharpens the focus of the needed detector development.

The most critical detector element is the solid-state vertex detector, with about a million channels and a 4π geometry to reconstruct tracks and vertices in 3-D. The experience at the Tevatron collider, will lead the way to the "best" approach for the SSC.

A detector concept for the Tevatron collider has been recently proposed. This is based around a large dipole magnet, with field transverse to the beam to maintain good momentum measurement for all charged tracks of $P_T < 5$ GeV/c. In addition to the silicon vertex detector, there will be a straw-tube tracking system, Ring-imaging Cerenkov counters for π-K-p separation, transition-radiation detectors and an electromagnetic calorimeter for electron identification and triggering, and a large farm of on-line numeric processors.

An R&D program has been initiated to address the many technical issues involved in building such a detector. An interim goal might be to place a portion of the vertex detector and tracking system in one of the low luminosity intersections at Fermilab during the 1991 collider run, in order to demonstrate that secondary vertices can be detected in a hadron-collider environment. Useful signals include $K^o_s \rightarrow \pi^+\pi^-$, and $D^o \rightarrow K^-\pi^+$.

The measurement of CP violation in the B system may be a distant goal but this drive allows many interesting features of the B system to be studied along the way: the details of $b\bar{b}$ production in hadron collisions, mixing, rare decay modes, etc. The combined prospects of new physics and an intermediate step toward high luminosity running at the SSC render the b physics potential of the Tevatron upgrade an important element of a healthy high energy physics program in the 1990's.

The $W^\pm$ the high rates in hadron collisions makes the Upgrade very competitive with LEPII for studying the physics of $W^\pm$. [5] One example of what might be done with the high rates at the Upgrade has recently been studied by the D0 collaboration. [6] The high statistics available in $W^\pm$ and Z^0 production at the New Tevatron permit the determination of the $W^\pm$ mass to a statistical precision comparable to that obtainable at LEPII. Using the value of the Z^0 mass obtained by LEPI or SLC a determination of the $W^\pm$ mass to a precision of ± 100 MeV/c^2 free of absolute energy calibration error may be achievable. [7] In the Standard Model with three generations, the mass of the $W^\pm$ depends strongly on the top quark mass and more weakly on the Higgs boson mass as shown in Figure 3. A precision measurement of the $W^\pm$ mass with an accurate measurement of the top quark mass enables one to test the consistency of the three generation Standard Model. Such a consistency check could be one of the first indicators of either a fourth generation or physics beyond the Standard Model(eg. Supersymmetry or Technicolor).

From Table 2, it is clear that detailed study of electroweak pairs will not be easy even with the Tevatron upgrade. The signal to background rate for $W^\pm$ plus two jets (with pair mass near $M(W)$) is not encouraging and the rate for totally leptonic channels is very small.

---

[5] 'Physics at LEP at Very High Energies', G. Barbiellini et. al., in 'Physics at LEP Vol. 2', edited by J. Ellis and R. Peccei, CERN Preprint 86-02, p.1 (1986).

[6] 'Theoretical Implications of the $W^\pm$ - Z^0 Mass Difference and the Capabilities of the D0 Detector in Measuring It', R.Raja, Fermilab preprint CONF-88/198 (1988).

[7] Ibid.

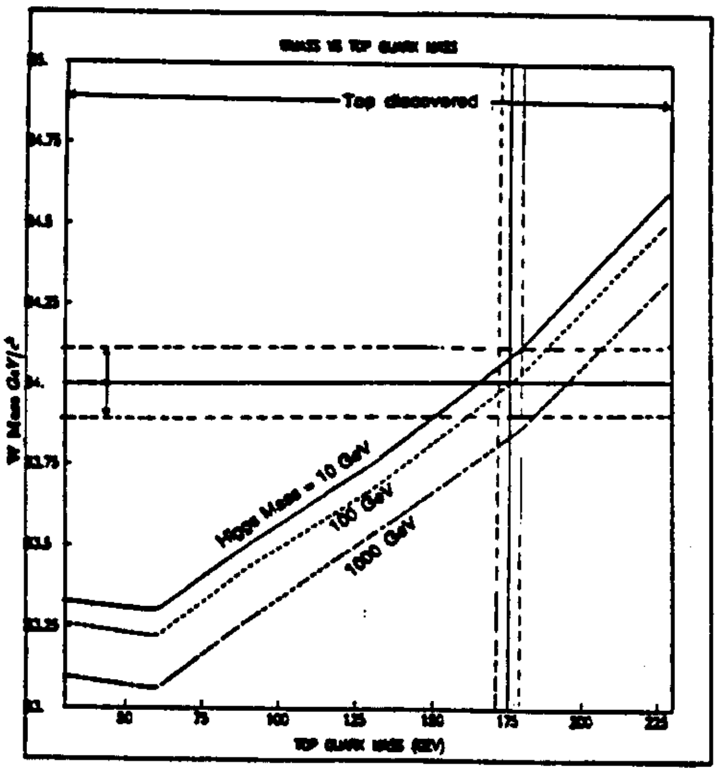

Figure 3:
Dependence of the W mass on the top mass for fixed Z^0 mass (Assumed here to be 94 GeV/c^2). The solid curve assumes the Higgs mass of 10 GeV/c^2; the dashed curve assumes the Higgs mass of 100 GeV/c^2; and the dash-dotted curve assumes the Higgs mass of 1000 GeV/c^2. The 1σ bands are shown for a top mass of 175 ± 5 and a W mass of $84.0 \pm .1$ are illustrated. (From Ref. 6)

However, there will be enough events (particularly in the W^+W^- channel) to look for any gross disagreement with the Standard Model prediction. For example, if the $W^\pm$ and Z^0 were composite, resonances might occur in electroweak pair production at high energy or the $W^\pm$ might have an anomolous magnetic moment. One can search for strong resonances or any other large deviation of the cross section in any of these channels at subprocess energies well above the highest LEPII energy. For example, resonances might occur in electroweak pair production at high energy if the $W^\pm$ and Z^0 were composite.

3.2 Minimal Extensions

The Tevatron energies are high enough to be sensitive to new physics at the electroweak scale. The simplest extension is the possibility of a fourth generation of quarks and leptons. If discovery requires 100 produced pairs a fourth generation quark could be discovered for masses up to 120 GeV/c^2 in the present run of the Tevatron. With the New Tevatron discussed above, the discovery limit for new quarks will be extended to 350 GeV/c^2. This range of masses is particularly important within the standard model. Figure 4 shows the bounds on new quarks implied by the standard model. If it is assumed that there is no new physics (beyond a fourth generation) all the way to the GUT scale ($\geq 10^{15} GeV$) then a more stringent unitarity upper bound can be obtained for quark masses. [8] As shown in Figure 4 the New Tevatron collider will be sensitive to any quark masses within the whole region allowed by these theoretical bounds.

New $W^\pm$ and Z^0 gauge bosons are required in almost any model which extends the standard model by unification. In models which restore a Left-Right symmetry at high energies additional charged weakly interacting gauge bosons are required ($W'^\pm$) [9] and in many unified models, including the presently popular E_6 model motivated by superstrings, neutral gauge bosons are required (i.e. Z'^0). [10] The strongest present limits on new $W'^\pm$ and Z'^0 come from deep-inelastic neutrino scattering experiments and require that the mass of any new boson with couplings similar to the couplings for the standard $W^\pm$ and Z^0 to be greater than 300 GeV/c^2. The cross section for a Z'^0 at the Tevatron and for the various Upgrade phases and the pp Option is shown in Figure 5. In its present run at the Tevatron, CDF will be able to discover a new $W'^\pm$ or Z'^0 with masses up to 400 GeV/c^2. With the New Tevatron masses up to 1200 GeV/c^2 can be discovered. This represents a very significant window on new physics.

Furthermore, if a $W'^\pm$ or Z'^0 was discovered at the present run at the Tevatron, the New Tevatron will allow detailed study of its properties. For a mass at the discovery limit of the present run (400 GeV/c^2), 18,000 events will be produced in a standard run at the Upgrade.

[8] C. Hill, Phy. Rev. D24, 691 (1981), and references therein.

[9] J. C. Pati and A. Salam, Phy. Rev. D10, 275 (1975); R. N. Mohapatra and J. C. Pati, Phy. Rev. D11, 566 (1975); R. N. Mohapatra and G. Senjanovic, Phy. Rev. D23, 165 (1981).

[10] For the properties of the additional Z^0 in E_6 models see, for example: V. Barger and K. Whisnant, *Proceedings of the Workshop: From Colliders to Supercolliders*, Madison, WI, May (1987) and Int. J. Mod. Phys. A3, 879 (1988).

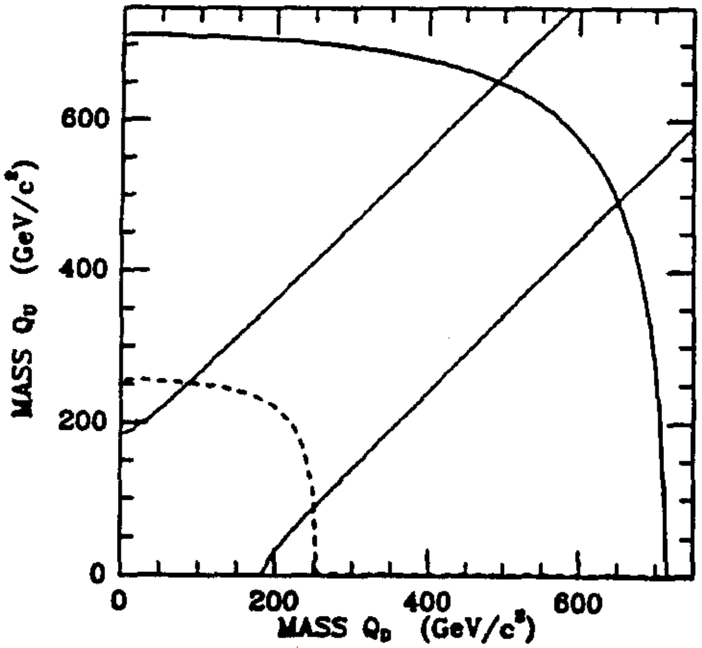

Figure 4:
Theoretical bounds on the quark masses of a postulated fourth generation. The pair of dotted diagonal lines give the upper bound on the magnitude of the Q_U - Q_D mass difference arising from bounds on the rho parameter. The solid curve gives the upper bound on the masses consistent with perturbative unitarity. Finally the dashed curve gives the bound arising from the assumption that perturbative unitarity will hold at all scales below the GUT scale. (See Ref 8 for more details).

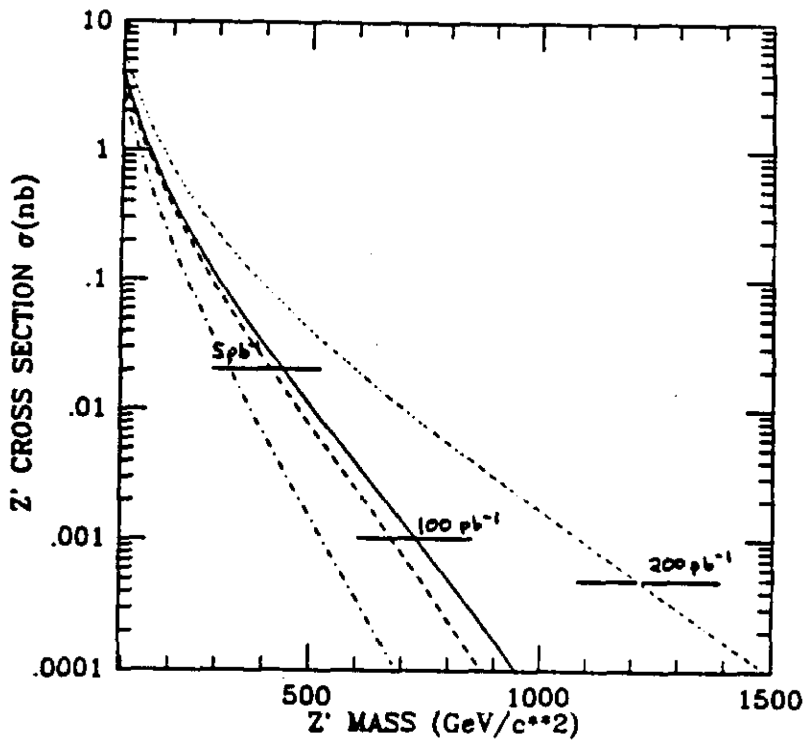

Figure 5:
Total cross section, σ(nanobarns), for the production of a new neutral gauge boson, Z'^0, in $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV (dashed curve), 2.0 TeV (solid curve), and 3.6 TeV (dotted curve); and in pp collisions at $\sqrt{s}$ = 2.0 TeV (dashed-dotted curve). The EHLQ parton distribution functions (with Λ = 290 MeV) were used. The couplings of the Z'^0 to quarks and leptons were assumed to be the same as the Z^0 couplings. The cross sections required to produce 100 Z'^0 events in a standard run of integrated luminosity of $5pb^{-1}$, $100pb^{-1}$, and $200pb^{-1}$ are indicated by horizontal solid lines. The cross section required with an integrated luminosity of $1000pb^{-1}$ is $.1pb$.

For comparison, Phase II extends the present discovery limit to 750 GeV/c^2. Because of the absence of valence antiquarks in pp collisions, the pp Option is not as powerful as the proposed Upgrade program in spite of the higher luminosity.

3.3 New Directions

Technicolor, supersymmetry, and compositeness are three major departures from the standard model which have received considerable theoretical attention. [11] In each of these models new physics is proposed for which the Tevatron collider program can make an important contribution.

In the simplest technicolor models one expects a number of light spinless particles associated with the technicolor interaction. These particles are called technipions in analogy with the lightest particles associated with QCD, the pions. Some of these technipions will be colored (e.g. P_3 and P_8) while others are color neutral (e.g. $P^{\pm}$, P^0, and P'^0). A detailed study of the possibilities for detection of these particles at the Tevatron [12] concludes that if the production of $P^{\pm}P^0$ pairs through the decays of $W^{\pm}$ is kinematically allowed the detection of these color singlet technipions should be feasible at the Tevatron. For the color triplets (and octets) the rates for the expected technipion masses is marginal in the present phase but would become quite feasible with the Upgrade. Recently a variation on the standard technicolor model called Walking Technicolor [13] has attracted considerable theoretical attention because of the possibility that these models may cure the flavor changing neutral current problems of the original technicolor based models. In this new class of models one also expects new particles in the mass range, (200 - 300) GeV/c^2, which could be discovered at the New Tevatron.

For supersymmetric theories the masses of the superpartners of the ordinary quarks, leptons, and gauge bosons are not presently determined by theory. However, there is an expectation that the general scale of these superpartner masses should not be much above the scale of the W and Z masses, i.e. of the order of a few hundred GeV. The cross section for pair production of gluinos (the superpartners of gluons) at the present Tevatron and the various Upgrade phases is shown in Figure 6. If 100 produced pairs are required for detection, in the present run CDF should be able to detect gluinos and squarks (the superpartners of the ordinary quarks) with masses up to 140 GeV/c^2 and in a standard run with the New Tevatron masses up to 360 GeV/c^2 could be detected. For comparison, at the completion of Phase II of the Upgrade, gluinos with masses up to 210 GeV/c^2 could be detected and with the pp Option the discovery limit in a standard run would be 270 GeV/c^2. Alternatively, if a gluino were found in the present run at its discovery limit (140 GeV/c^2), a standard run at the Upgrade would produce 72,000 gluino pairs.

[11] For a review of possible new physics and applications to the Tevatron Collider see, for example: E. Eichten, "Theoretical Expectations at Collider Energies", Fermilab - PUB - 85/178-T (1986).

[12] E. Eichten, I. Hinchliffe, K. D. Lane, and C. Quigg, "Signatures For Technicolor", Physical Review, D34, 1547 (1986).

[13] T. Appelquist, D. Carrier. L. C. R. Wijewardhana, and W. Zheng, Phy. Rev. Lett. 60, 1114 (1988), and references therein.

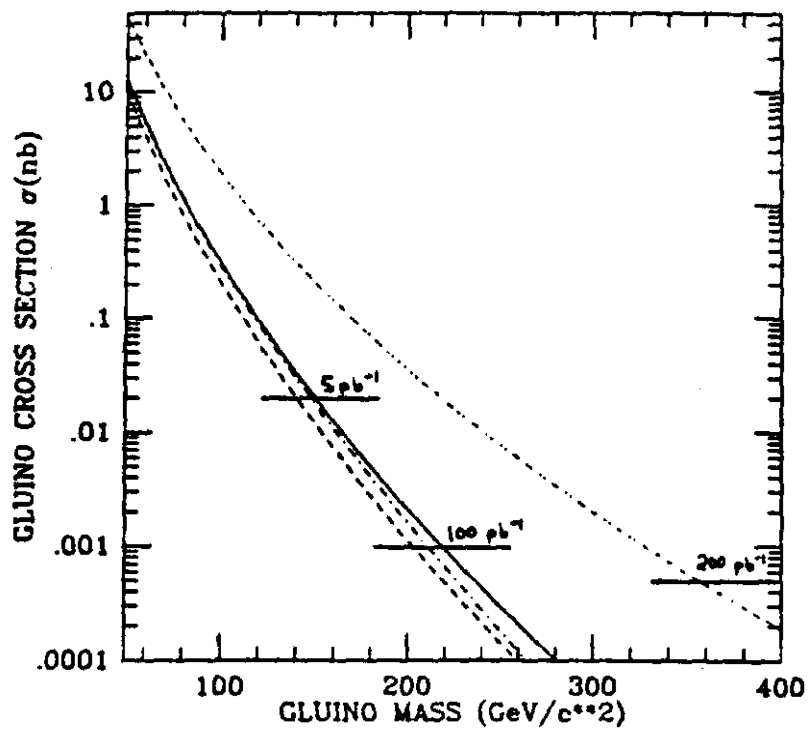

Figure 6:

Total cross section, σ(nanobarns), for the production of gluino pairs in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV (dashed curve), 2.0 TeV (solid curve), and 3.6 TeV (dotted curve); and in pp collisions at $\sqrt{s} = 2.0$ TeV (dashed-dotted curve). A rapidity cut of $|y| < 1.5$ was applied two both final gluinos. The EHLQ parton distribution functions (with $\Lambda = 290$ MeV) were used. The cross sections required to produce 100 gluino pairs in a standard run of integrated luminosity of $5pb^{-1}$, $100pb^{-1}$, and $200pb^{-1}$ are indicated by horizontal solid lines. The cross section required with an integrated luminosity of $1000pb^{-1}$ is $.1pb$.

Table 3: Discovery Limits for New Physics

	Discovery Limit (GeV)		
	Now	Phase II	Phase III
Heavy Quark	120	220	350
Z'^0 or $W'^{\pm}$	400	720	1200
Gluino	140	210	360
P_3 Technipions	125	230	360
Quark Substructure	1400	2300	3200

Finally, the systematic study of QCD jet physics will be possible up to very high jet pair masses. In the present CDF run at the Tevatron, approximately 100 jet pair events should be observed with pair masses in excess of 500 GeV/c^2. In a standard run with the New Tevatron, 100 jet pair events should be observed with a pair mass in excess of 1,000 GeV/c^2. This allows the possibility of testing quark compositeness up to a compositeness scale of 1.4 TeV in the present run and in a standard run with the New Tevatron scales up to 3.2 TeV can be probed. The corresponding limit is 2.3 TeV at the completion of Phase II of the Upgrade and 2.7 TeV for the *pp* Option.

3.4 Summary of Collider Physics Motivations

The Tevatron collider will provide a wealth of physics opportunities within the standard model. With the Upgrade, detailed studies will be possible for the electroweak gauge bosons, jets, and heavy quarks. In particular, within the Standard Model the discovery of top is assured and if the mass is low enough that top is discovered soon then the Upgrade has the potential to be a top factory. More than 10^{10} bottom quarks will be produced in a single run at the Upgrade. This is 1000 times the rate available in e^+e^- collisions at an upgraded CESR in 1995. The Upgrade provides an appropriate environment in which to tackle the difficult problems of tagging and studying rare B decays in a hadron collider. With clever ideas and hard work the large numbers of $W^{\pm}$ and Z^0 electroweak bosons produced (Table 2) can be used the test the Standard Model and perhaps even get some indirect suggestion of the Higgs boson mass. These opportunities alone guarantee a successful physics program at the proposed Upgrade.

Secondly, the Upgrade will extend the discovery limits by a factor of two for: new quarks associated with a fourth generation, new electroweak gauge bosons associated with a partial unification of the gauge interactions, or gluinos and squarks associated with supersymmetry. It will also greatly extend the range in the search for new fundamental interactions such as Technicolor or quark compositeness. These results are summarized in Table 3.

Furthermore, signals of new physics which are at the discovery limit of the present run of CDF at the Tevatron collider could be studied in detail with the New Tevatron. Table 4 illustrates this by comparing the production rates for a Z'^0 or $W'^{\pm}$, gluino, and technipion

Table 4: Factory Domain

Particle	Mass(GeV/c^2)	Events in a Standard Run		
		Now	Phase II	Phase III
Z'^0 or $W'^{\pm}$	400	100	3.1×10^3	1.8×10^4
Gluino	140	100	4.0×10^3	7.2×10^4
P_3 Technipions	125	100	3.0×10^3	3.0×10^4

at the various Upgrade options, for the mass at the discovery limit of the present run at the Tevatron.

Finally, although a full understanding of the physics of the one TeV scale will require the SSC, the Tevatron may provide important clues to the character of this new physics. These signals are typically associated with very rare events and thus an extended effort at high luminosity will be required to discover any such signal. Clearly this phase of the Tevatron collider physics program would benefit greatly from the proposed Upgrade program.

3.5 The Tevatron Fixed–Target Program

When the source of protons for the fixed-target program changed from the Main Ring to the Tevatron, a number of profound changes were set in motion. These changes are making heavy quark physics the major focus of the fixed-target program. It is by no means the only focus of the experimental effort. The changes that the Tevatron brought about are summarized breifly in the following.

The primary proton energy increased from 400 GeV to 800 GeV and this led to a corresponding increase in the useful energy of secondary and tertiary beams from roughly 150 GeV to 300 GeV. Certain beams such as π^- and μ^+ beams now have intense fluxes at 500 GeV. The macroscopic duty factor, the ratio of the time during which primary beam is delivered to a target to the duration of the accelerator cycle time, increased from 12% to 40%. These changes combined with advances in the performance of microvertex detectors and data acquisition systems made the detection and background free reconstruction of particles containing heavy quarks feasible. Microvertex detectors made it possible to distinguish the decay vertex of a heavy quark decay from the primary interaction vertex thereby making the assignment of charged particles to the decay vertex unambiguous. Prior to these changes, fixed-target experiments attempting to observe charmed particles detected at most a few hundred events with considerable background. Today, the most accurate measurements of charmed particle lifetimes come from E-691, a Fermilab photoproduction experiment that took data in 1985. This experiment, which observed a total of somewhat more than 10,000 fully reconstructed charm decays, also provided the world's most precise data on such diverse topics as $D^o\bar{D}^o$ mixing and excited states of charmed mesons and baryons. The ability of E-691 to separate charmed particle decays from the general background of hadrons is shown in Figure 7 which is a mass plot of 3400 fully reconstructed events with well-identified decay vertices in a single decay channel. The significance of the "E-691 break through" is profound

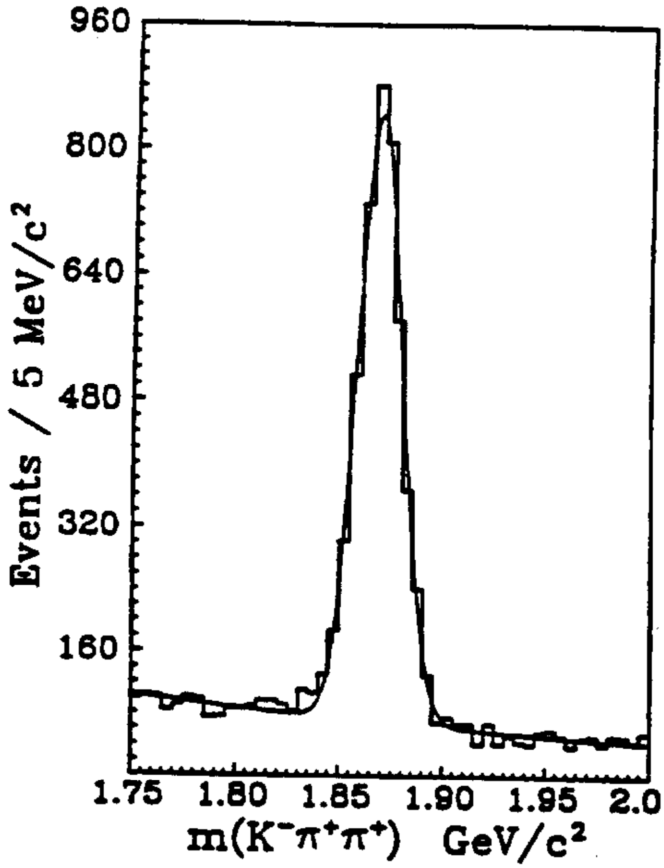

Figure 7: Mass distribution of charmed particle decays from Fermilab experiment E-691.

for the future of hadron physics. It took about a decade to solve the problem of obtaining clear signals out of a background in which charm production is only 0.1%. Machine performance, detector technology and data processing power were the key elements. Obviously this success encourages the next stage; beauty physics.

Since that experiment was completed in 1985, two new multiparticle spectrometers with more accurate microvertex detectors, improved particle identification, and more effective data acquisition systems have been commissioned. Two additional facilities will be upgraded with microvertex detectors in 1989. Some of these facilities will be capable of observing more than 10^6 fully reconstructed charmed particles and all are intended to obtain roughly 1,000 partially reconstructed beauty particles with well-identified decay vertices. Typically 50 beauty particles should be fully reconstructed in each experiment.

When both the 400 MeV linac and the Main Injector are operational, the number of protons per pulse could increase by a factor of three above the typical intensity achieved during the 1987-88 fixed target run. Even without improvements in detectors the heavy quark experiments should acquire three times as much data as will be obtained in the 1989-90 fixed target run. With improvements to the detectors both the fraction of b's that can be fully reconstructed and those that can be partially reconstructed should increase significantly.

The increased intensity will also allow more accurate measurements of CP violation in the $2\pi^o$ and the $\pi^+\pi^-$ decay modes of neutral kaons. Already the data from the 1987 run of E-731 should yield a measurement of ϵ' to an accuracy of 25%, if it is truly as large as 0.0035. The same data has already produced a limit on the K_L^o branching ratio to $\pi^o e^+ e^-$ of 10^{-9}. More accurate experiments will be possible with the Upgrade, for example it should be possible to reduce the error on ϵ' by another factor of 2 and to make a measurement of η_{+-o}, the parameter that measures the strength of CP violation in the decay of K_S^o into $\pi^o\pi^+\pi^-$, to an accuracy of a few parts in ten thousand. During the period from now till the end of 1992, there should be two fixed target runs each of eight-month duration, exclusive of startup and shutdown. The experimental program for these runs includes the following experiments:

1. An experiment will fully reconstruct several $\times 10^5$ charmed particles and 100 b particles, and partially reconstruct several thousand b particles from all produced in the photoproduction at an average energy of 225 GeV. These results should provide measurements of the lifetimes of the neutral and charged heavy flavor mesons and accurate measurements of the differential photoproduction cross sections of B mesons and baryons. Rare decays of charm at the level of 10^{-6} should be identified and in so doing the limit for $D^o\bar{D}^o$ mixing should be reduced by another order of magnitude. Accurate measurements of the semileptonic branching ratios of charmed mesons should be obtained. These will in turn improve the accuracy of the $|V_{cd}|$ and $|V_{cs}|$ elements of the KM matrix.

2. Five experiments dedicated to the production of b particles in hadron beams should take data. Each of these experiments is expected to be able to separate b's from other processes by observing the b decay vertex and by this method reconstruct a few tens to a few hundred b's. Given their different emphasis on kinematics, collectively they should provide an extensive picture of hadroproduction of heavy quarks. Some of these experiments will also acquire in excess of 10^5 charmed particle decays.

3. A measurement of the phase of η_{oo} to an accuracy of 1 degree and a reduction of the lower limit on the branching ratio of $K_L^o \rightarrow \pi^o e^+ e^-$ to 10^{-11}.

4. A measurement of nuclear structure and fragmentation functions in inelastic muon scattering. The range of q^2 will be from $0.2(GeV/c)^2$ to $100(GeV/c)^2$ and the range of X_{BJ} will be from 0.001 to 0.2.

5. A measurement of direct photon production in the collisions of 530 GeV mesons of both signs with Be nuclei and 800 GeV protons with Be nuclei will provide a comprehensive survey of direct photon production in hadron collisions. This experiment together with the planned measurements of photoproduction cross sections of heavy flavors and jets will be sensitive to the gluon distribution functions of the nucleon.

6. An experimental measurement of the asymmetry parameter of the Σ^+ decaying into p + γ will be made by observing in excess of 10^5 events. At the same time a search will

be made for the previously unseen decay $\Xi^- \rightarrow \Sigma^- + \Upsilon$. If the branching ratio is as large as expected a sample of several thousand radiative decays of the Ξ^- should be observed.

7. An experimental measurement of the Ω^- magnetic moment to $\pm$ 0.04 nuclear magnetons will be made, thus completing the measurement of all strange hyperon magnetic moments including the Σ^o - Λ^o transition magnetic moment to similar or better precision.

8. An experiment dedicated to the detection of charmed baryons with non-zero strangeness produced by a hyperon beam of Σ^- and Ξ^-.

These experiments are noted because follow up experiments of this type will benefit significantly from the first two stages of the Upgrade. The gradual increase in beam intensity that accompanies the first two phases of the Upgrade will increase the number of detectable b particles to the level where there are of the order of 100 events per decay mode. That gradual increase will be well matched to the detector and data acquisition development that will proceed in parallel, if the produced b's are to be detected and analyzed.

While the present generation of these experiments will be completed before the new Tevatron can be used to produce higher energy secondary and tertiary beams with adequate intensity, the motivation to do many of these experiments more accurately will remain because of the fundamental nature of these measurements. It has been 25 years since it was established that the decay of K_L^o did not conserve CP. Shortly thereafter it was recognized that ϵ' was an important parameter to measure. Time has only enhanced its importance.

The higher energy secondary and tertiary beams produced by the new Tevatron will provide another factor of 10 increase in the yield of b particles. Table 5 shows how the intensity of each type of secondary beam will improve between 800 GeV and 1500 GeV. Just as charmed particle production has a niche, beauty production may have a similar one for the same reasons: vertex detectors and ring imaging Cerenkov counters are much better adapted to the geometry of fixed-target experiments than they are to Collider experiments. It is possible that a fixed-target search for meson decays in which there are no D's in the final state may be freer of systematic errors than similar experiments done at e^+e^- colliders. Particle identification and vertex identification might allow the separation of mixing in the neutral B meson system from the neutral B_s system if adequate intensities can be produced. Some of the spectrometers have been designed to handle interaction rates in excess of 1 GHz. At the very least the systematic errors of fixed-target experiments will be very different from those of e^+e^- colliders and hadron colliders and these important parameters deserve more than a single measurement.

The acquisition of data on high energy neutrino interactions using beams produced by 800 GeV protons is now reasonably mature. Until data taken during the 1984-85 and 1987-88 fixed-target runs are fully analyzed, the next step in high energy neutrino experiments with the limited flux of protons that can be provided by the Tevatron is uncertain. More accurate measurements of the ratio of charged to neutral currents are feasible if the intensity of the Tevatron can be pushed well beyond the standard intensities achieved during the

Table 5: Comparison of secondary beam yields between 800 GeV and 1500 GeV

Particle	Average particle energy	Ratio of yields at 1500 GeV and 800 GeV
e^-/γ	350 GeV/225 GeV	5
π^-	600 GeV	12
μ^+	600 GeV	8
K_L^o	120 GeV	2

1987-88 fixed-target run. These measurements could lead to much better measurements of $sin^2\theta_W$ if the effect of charmed particle production can be accounted for accurately. An experiment that could provide data on this issue is mentioned in section 3.6.2. One of the best constraints on the electroweak radiative corrections is the comparison of $sin^2\theta_W$ measured in neutrino experiments and the W to Z mass ratio measured in high energy collider experiments. These measurements, together with measurements of the KM matrix elements involving b-u transitions, and the mixing parameters in the neutral B mesons severely constrain the mass range in which the elusive top can hide.

Deep inelastic muon scattering may offer the best hope to measure nucleon structure functions in the range relevant to Tevatron Collider experiments. The new Tevatron will increase the muon intensity at 550 GeV by more that a factor 10 compared to the intensities currently available. This makes an experiment with a range $1 < Q^2 < 500 GeV^2$ possible. The range is significant since the scaling violations are logarithmic. A first observation of the variations of α_s with Q^2, the running of the coupling constant, should be the goal of such an experiment. With the extra complexity of the measurements due to the interplay of the weak and electromagnetic interactions, such a measurement at HERA will be very difficult. Further the importance of measurements on different nuclear targets to our understanding of QCD has been emphasized in recent years and such measurements are almost uniquely the domain of fixed-target experiments.

3.6 Physics with the Main Injector

3.6.1 Kaon Physics with the Main Injector

One of the important characteristics of the new Main Injector of Phase II of the Upgrade is its high energy coupled with high intensity. It is natural to examine its potential as an intense source of high energy kaons for precision studies of CP non-conservation as well as rare decay searches with high sensitivity. Such experiments are important in that with enough sensitivity very high mass scales can be accessed. The extracted beam from the Main Injector at 120 GeV will produce a source of high energy kaons that will not be surpassed in intensity, even in the SSC era.

The attention at Fermilab in kaon physics has recently been concentrated in precision studies of the $K_L \rightarrow 2\pi^o$ decay (ϵ'/ϵ), a search for the mode $K_S \rightarrow \pi^+\pi^-\pi^0(\eta_{+-0})$, and a search for the $K_L \rightarrow \pi^o e^+ e^-$ decay which is very likely CP violating to lowest order. At present, the Fermilab experiments have the greatest sensitivity for these modes even though the kaon production cross section is roughly independent of energy and at BNL, where the available proton flux far exceeds that of Fermilab, there is a dedicated program pursuing rare kaon decays. The advantage for these and other modes arises primarily from the higher energy of the decay products.

How might the field of kaon decays likely evolve? Briefly, the best searches for the lepton number violating decays come from BNL experiments and these are now at the 10^{-10} level. Additionally, the interesting mode of $K^+ \rightarrow \pi^+ +$ "*nothing*" seems to be best done with a stopped charged kaon beam and there BNL has the best experiment. Both of these efforts could probably be upgraded to the 10^{-11} level or perhaps better with the Booster/Stretcher combination proposed there.

At the Tevatron, the $K_L \rightarrow \pi^o e^+ e^-$ sensitivity can also be pushed to nearly the 10^{-11} level and the (statistical) sensitivity to ϵ'/ϵ is now at the level of 0.0004, corresponding to over 0.5×10^6 detected $K_L \rightarrow 2\pi^o$ decays.

The next generation of experiment in the 2π system will likely require over $10^8 K_L \rightarrow 2\pi^o$ decays with very little background; such a sample would permit a measurement of ϵ'/ϵ with a precision of better than 10^{-4}; this is a level where the Standard Model would certainly be definitive in its non-zero prediction. Closely coupled with the issue of a non-zero ϵ'/ϵ is the branching ratio for the $K_L \rightarrow \pi^o e^+ e^-$ mode which is expected to be of the order of a few times 10^{-12}. So far, although this mode has been the subject of wide interest, there has been little serious consideration of the issues required to obtain this sensitivity. Although this issue cannot be addressed in detail here, it is important to point out that with an extracted beam from the new injector, the flux necessary to permit sensitivities to this mode in the range of 10^{-10} per hour of running is obtainable. Furthermore, the Main Injector will be the best place to perform such experiments of any presently existing or planned facility.

The advantages of the Main Injector for the kaon physics discussed above can be illustrated with an example beam and high acceptance detector design (shown in Figure 8) which would be appropriate to address the arena of CP violation and rare kaon decays with very great sensitivity. The 120 GeV proton beam, with an intensity of 3.0×10^{13} at a 3.8 sec. cycle time (a variant of the high intensity Main Injector mode), strikes a Be target at about 20 mr. This is chosen in order to reduce dramatically the neutron flux in the beam relative to neutral kaons, even though in fact the neutral beam will be transported through the detector in vacuum. There follows 25 m of magnetized beam dump with collimation and shielding. The decay region is 20 m in length and the detector has a cross-sectional area of 3 m $\times$ 3 m. This model experiment concentrates on the flux greater than 15 GeV for a variety of reasons which will be given below; the solid angle of the beam is 36 μstr which results in a relatively small hole (dead region) in the detector.

The acceptance of the detector for the $\pi^0 e^+ e^-$ mode is 16% with the requirement that both photons exceed 1 GeV, and the decay rate for kaons between 15 and 50 GeV is 3.3×10^7 per sec. With a duty cycle of 50%, the sensitivity will be about 10^{-10} per hour. This should be compared to the current best sensitivity in a kaon experiment of about 10^{-10} per experiment.

The above beam design is conservative: there is a great deal more flux available were

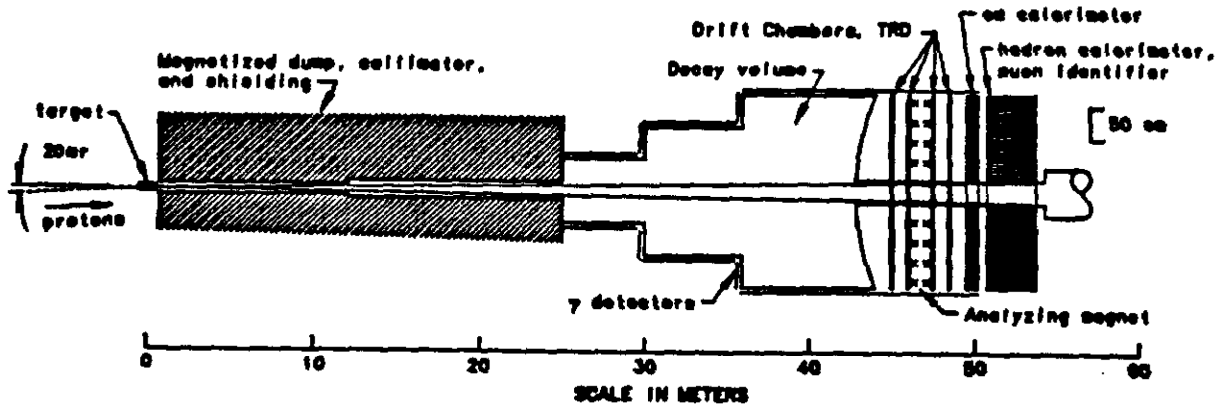

Figure 8: Model Neutral Kaon Apparatus using the Main Injector

one to employ a beam of greater solid angle. In addition, it may be possible to equip the beam hole region with active detectors and this would increase the acceptance. Thus in the future, there is the potential for even more sensitive measurements although the proposed sensitivity of the relatively modest configuration is already quite an advance.

First it should be stated that there are major experimental hurdles in actually obtaining such a sensitivity. An absorber 25 m in length is sufficient to reduce the flux of target muons to well below the level of singles rates from the kaon decays themselves; they will be governed by the total decay rate in the decay volume which will be 1.3×10^{6} per sec. at the above intensity. It is important to note that this rate is only four times the decay rate for the high energy region of interest, namely the decay rate for decays about 10 GeV. While not every decay will be counted, the singles rates will be on the order of 10^{6} per second! Clearly it will be important that any beam structure on 1 ns time scales be greatly reduced. This rate is the same as expected at the SSC with one important difference: multiplicity; kaon decays produce one or two particles, significantly less less than at the SSC. The chambers will need to be very high precision and fine-grained, probably with 2 mm wire spacing. The electromagnetic calorimeter will also need to be very finely segmented, consisting of about 20,000 cells of high resolution, radiation hard material. Another important feature of the detector is its ability to detect low energy photons which miss the aperture of the calorimeter. This feature has been important in the Fermilab experiments and it directly affects the background level for the rare decays. The neutron flux will be about 1.9×10^{9} per sec.

Since the kaon (and neutron) cross sections roughly scale, one could in principle do this physics at a lower energy machine. To operate at a 30 GeV machine, one would move four times closer to the target and accept decays greater than 4 GeV with a low energy threshold of 250 MeV. In practice, this is much less desirable than the configuration at the higher energy machine for the following reasons:

1. The resolution of electromagnetic calorimeters will be dominated by a term proportional to $1/\sqrt{E}$ so that the higher the energy the better the resolution and resolution is at a premium in such experiments.

2. The background of minimum ionizing particles does <u>not</u> scale with energy: a muon will simulate about 600 MeV energy deposit in an electromagnetic calorimeter so that it will be difficult to maintain the same relative threshold level as one decreases the energy. Note that for the round of $2\pi^o$ experiments of a few years ago, at the Tevatron the threshold energy was 2 GeV while at BNL energy, the threshold was 1 GeV.

3. Since the growth of hadronic showers is governed by $\ln(E)$ rather than linear in E, one can get away with a fractionally smaller beam dump region at the higher energy facility. As an important consequence, one can be situated relatively closer to the target and thus be much more sensitive to K_S decays. This opens up another realm of physics including CP violation in 3π decays and other rare K_S decays (including $\pi^o e^+ e^-$). Also, it may be necessary to observe the interference between the K_L and the K_S decays to the $\pi^o e^+ e^-$ mode to establish a CP violating effect.

4. The importance of the ability to reject events with soft photons outside of the aperture of one's electromagnetic detector in reducing background has already been mentioned. Again, the dominant problem with a low threshold will be the (non-scaling) minimum ionizing background.

These advantages make the Main Injector the best place to perform such kaon rare decay experiments.

3.6.2 Medium Energy Neutrino Experiments

Neutrino experiments have been an important part of the fixed-target program since the Main Ring started operation in 1972. There is a great opportunity to do significant neutrino experiments with the Main Injector as the following examples will show.

By using a lithium lens to focus positively charged mesons, an intense neutrino beam with a small but measurable antineutrino contamination can be produced with 120 GeV protons. Figure 9 shows the expected event rate with such a beam for a 1 ton target and 2×10^{19} 120 GeV protons on target. The Main Injector operating at a repetition rate of 3 seconds could deliver this flux in 560 hours or just under six weeks of operation. Such an event rate would extend the limit on the mixing angle between the ν_μ and ν_τ to .01 radians for ν_τ masses greater than 30 eV.

A target consisting of 1 Ton of emulsions embedded within a multiparticle spectrometer would allow the identification of ν_τ interactions through the identification of the τ decay

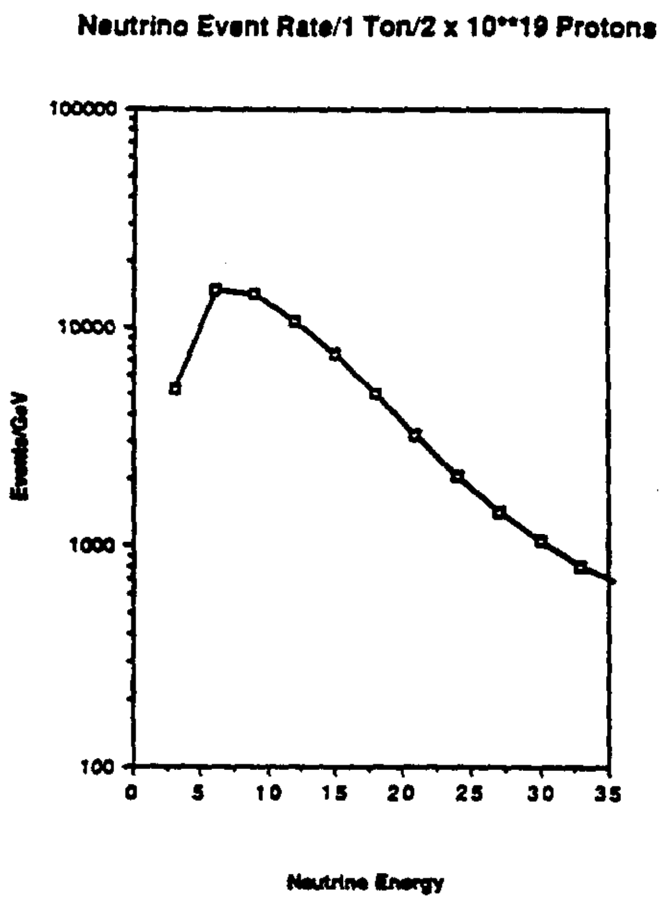

Figure 9: Charged current event rate for a 120 GeV high flux neutrino beam. Calculation assumes a 0.75 m radius detector, a 400 m decay pipe, 120 m shield, and a focussing system which is 50% efficient.

vertex. The best limit on this transition comes from E-531, a neutrino experiment done at Fermilab between 1979 and 1980 using a 100 kg emulsion target. Since the τ events would be found in the "neutral current" events, the background in this sample would be charmed particles produced by neutral currents. These events together with the charmed particle events produced by charged current interactions are interesting in their own right. This sample of charmed particles could be used to significantly reduce the largest uncertainty in the measurement of $sin^2\theta_W$ obtained from the ratio of neutral current interactions to the charged current interactions in deep inelastic neutrino scattering.

Such a beam will also make it possible to make accurate measurements of the $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ cross sections. A detector with a 200 ton fiducial volume could detect more than a thousand $\nu_\mu e^-$ interactions for 2 x 10^{19} protons on targets. The neutrino energy range of 5 to 35 GeV is in many ways ideal for the measurement, because the electron recoil momentum is in roughly the same energy range. Electrons in this energy range are easily distinguished from charged $\pi's$ and yet the neutrino energy is low enough so that coherent π^o production on nuclei by neutrinos can be distinguished from $\nu_\mu e^-$ interactions. Such an experiment could give a very accurate measurement of $sin^2\theta_W$ at an average q^2 of about .01 $(GeV/c)^2$. The same experiment would produce ten million charged current events and several million neutral current events. Thus, a second very accurate measurement of $sin^2\theta_W$ could be made at an average q^2 of about 1 $(GeV/c)^2$, if it were combined with the charm production data of the emulsion experiment.

3.6.3 Medium Energy Antiproton Experiments

In addition to the kaon and neutrino experiments, the Main Injector will substantially improve the experiments which now use the Main Ring to produce secondary beams such as the search for undiscovered states of charmonium. This experiment measures the cross section for the resonance formation of charmonium states in $p\bar{p}$ collisions followed by the inclusive decay into a J/ψ. Antiprotons are produced by 120 GeV protons and stored in the Antiproton Source in the same way as is done for colliding beams. Since the Antiproton Source is dedicated to providing antiprotons to the Tevatron during collider runs this type of experiment can run only during the fixed-target running periods. The Antiproton Source Accumulator Ring, the location of the experiment, is a unique facility because of its energy and beam quality. A small detector enclosure was constructed in one of its straight sections in 1986. In 1988 a gas jet was installed in the same location and was used to observe collisions of a circulating beam with a hydrogen gas jet. The useful energy range, 2 GeV/c to 8.8 GeV/c, of the circulating antiproton beam will make it possible to search for all charmonium states between 2950 MeV/c^2 to 4000 MeV/c^2 as well as states as light as the ξ (2240). An experiment built to search for the undiscovered states of charmonium and to measure the masses and widths of the established charmonium states will take data for the first time during the 1989-90 fixed-target run. Since the momentum spread of the beam is expected to be less than 2 MeV/c (FWHM), the widths of states as narrow as 500 KeV/c^2 (FWHM) can be measured directly.

A luminosity of $10^{31}cm^{-2}sec^{-1}$ can be achieved with 15 x 10^{10} antiprotons and under these conditions a beam lifetime of 20 hours or more is expected. While a larger number of antiprotons can be stored in the Accumulator, up to 80 x 10^{10} have been stored during collider operation, it does not appear practical to do this during fixed-target operation. The reason for such an extended fill time is that the performance of the Main Ring at injection is sensitive to the stray magnetic fields of the Tevatron, which vary continuously throughout the fixed-target cycle. As a result a broad search over the full range of charmonium masses for unexpected states cannot reach the critical level of sensitivity, because the luminosity will be limited to about $10^{31} cm^{-2} sec^{-1}$. Because the Tevatron would not interfere with the Main Injector, the Accumulator could be filled at almost $10^{11}\bar{p}$/hour. With such a fill rate luminosities of $5 \times 10^{31} cm^{-2} sec^{-1}$ would be feasible and searches for the unexpected states with a sensitivity of 0.5 events/$(pb^{-1} - MeV/c^2)$ could be carried out in a run of 2,500 hours.

3.6.4 Operating Modes for the Main Injector

It is worth noting here how such a diverse program of physics with the Main Injector might be carried out without impacting either the fixed-target program or the Collider program. During fixed-target operation the Main Injector cycle could be set at 4 seconds with a 2 second flat top. During each Main Injector cycle 6 Booster batches would be accelerated to 120 GeV. If the Antiproton Source were being filled one batch would be extracted and sent to the Antiproton Source to make $\bar{p}$'s, and the remaining 5 batches would be debunched, subsequently extracted over the next two seconds, and sent to the neutral K target in the Neutrino Area. With this cycle the $\bar{p}$ stacking rate would be 5 x $10^{10} hr^{-1}$ and the proton flux to neutrino would be reduced by 16%. When filling was not in progress, all of the intensity could go to the Neutrino Area. Since the Tevatron must be filled for fixed-target operation two Main Injector cycles of 2 second duration with 150 ms flat top would be needed. Thus a typical supercycle of 64 second duration would consist of two 2 second Main Injector cycles to fill the Tevatron, followed by fifteen 4 second Main Injector cycles for the K_L^o experiments and the medium energy $\bar{p}p$ experiments. During slow extraction from the Tevatron, typically 23 seconds in duration, high energy proton beams, 800 GeV or 1500 GeV, would be transported to the Proton Area, Muon Area, and Meson Area simultaneously with the transport of 120 GeV protons to the Neutrino Area.

During collider operation there would be a premium on maximizing the repetition rate for $\bar{p}$ production. In this case there would be a 2 second cycle, with a 250 ms flat top. Again the Main Injector would be filled with 6 Booster batches. Again one batch would be extracted for $\bar{p}$ production at the start of the flat top and the other 5 would be extracted at the end of the flat top and sent to a neutrino beam target in the Neutrino Area. By extending the flat top on every fourth pulse and slowly extracting some of the beam, protons could be supplied to test beams in Proton, Muon, and Meson. Of course this is done at the expense of a somewhat reduced $\bar{p}$ stacking rate for colliding beams. A large variety of Tevatron supercycles such as the aforementioned are already a standard feature of operation. These examples are presented to show that it can be done easily.

In summary the use of the Main Injector will allow an emerging physics program based on 120 GeV protons to become much more effective since it will decouple acceleration and extraction of these protons from the Tevatron without compromising the fixed-target program or the collider program.

4 The New Tevatron

The New Tevatron exploits the full potential of the Main Accelerator complex with a new ring of high field, superconducting magnets replacing the old Main Ring. Phase III doubles the energy and luminosity achieved by the Phase I and II upgrades and greatly extends the physics reach, as shown in Tables 2 through 4. Since the New Tevatron requires the longest lead time and has the largest cost, it will be discussed first, with the Main Injector and the Phase I upgrade being described in subsequent sections.

4.1 Accelerator Issues

The dominant design issue is the superconducting bending magnet to be used in the new ring. Since the overall geometry is fixed by the existing tunnel, the achievable energy is determined by the dipole magnet field. At 1.5 TeV, the required field is 6.6 Tesla and the magnet design is relatively straightforward, representing a continuation of the Tevatron, HERA, SSC line of progress. At 1.8 TeV, 8 Tesla is needed. With present technologically well-developed superconducting materials, 2 K refrigeration is implied. Since the magnet aperture must be large enough to satisfy the demands of slow extraction in fixed target operation and separated orbits in the collider mode, the resulting stresses are approaching material yield strengths. The next subsection comments on the R&D program appropriate to the design of the dipole magnet.

The quadrupoles currently in production for the B0 and D0 interaction regions are capable of excitation at a field gradient of 140 T/m. The higher energy operation implies a redesign of the interaction region optics; in order to achieve the focussing appropriate to $\beta^* = 0.5m$, the quadrupoles may need to move further into the detectors than is the case at present.

An R&D effort will also be needed for the cryogenic system. The 1.8 K implementation will be facilitated by the minimization of the lowest temperature cold mass in the design of the magnets. Current estimates indicate that each watt removed at 1.8 K requires a factor of seven more compressor power than one watt at 4.2 K.

With the replacement of the Main Ring by the Main Injector in a separate enclosure, a candidate for a third interaction region becomes available — namely, E0. In the plan as outlined here, this location is not developed as a high luminosity collision point with facilities for a major detector. Quite aside from the costs associated with such a step, the separator scheme would become much more complex. If such a separator arrangement could be designed, then high luminosity physics could be conducted at E0. Smaller lower luminosity experiments can continue to be performed at C0 and E0 during running time scheduled with the separators off. This is the situation presumed in this report. It is worth noting that the utility of these regions for experimentation will be substantially improved by the Upgrade because the space used by the Main Ring for abort and transfers to the Tevatron will be removed from these areas.

The main motivation for potential lattice modifications in the new Tevatron is to simplify the separator problem. From CERN experience, the separator scheme that is underway in Phase I calls for a beam separation of 5 times the rms beam size. In order to avoid doubling the separator strength in the new Tevatron, lattice modifications are being investigated that

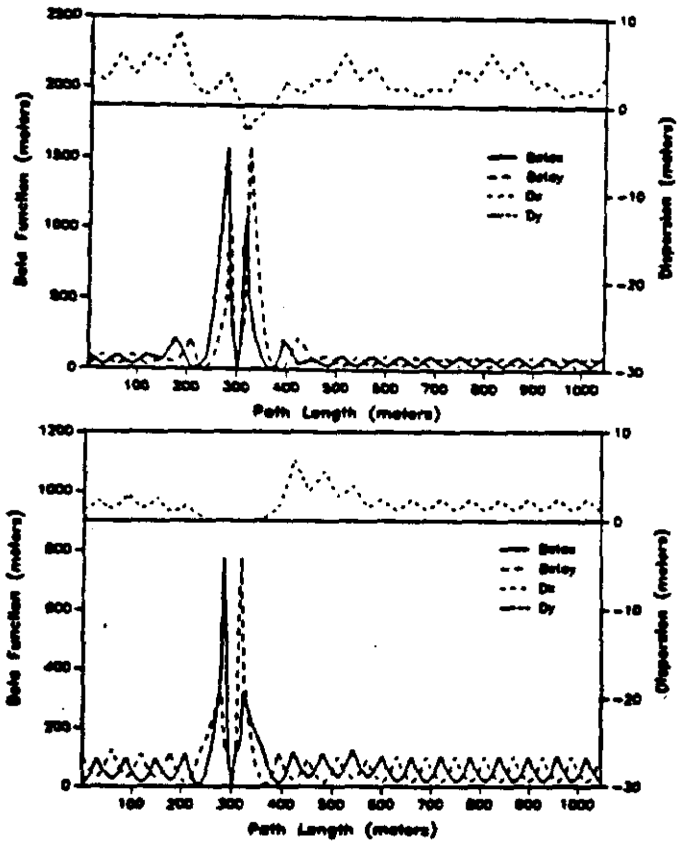

Figure 10: The upper plot shows the present Tevatron lattice functions. The lower plot shows those of the New Tevatron.

will reduce the beam size. The status of this effort is summarized in Table 6 and Figure 10. A combination of higher betatron oscillation phase advance in the standard cells and a match of optical properties of the long straight sections to the standard cells has significantly improved the amplitude and dispersion functions. This work is still in progress.

4.2 High Field Magnet Program

The goal of the high field magnet program is to produce a magnet capable of supporting the fixed target operation (ramping, resonant extraction) at a field of 6.6T and colliding beam physics at 8.0T corresponding to energies of 1.5 TeV and 1.8 TeV respectively. In order to achieve peak fields of this level (8.0T) the magnet temperature must be maintained at ≈ 2.0 K; the 6.6T operation will take place at 4.2 K. The ac heat load (≈ 400W) on the cryogenic system, due to the hysteretic losses in the iron and the superconductor associated with the continual ramping of fixed target operation, precludes the lower temperature/higher energy in this mode.

In a similar manner to the existing Tevatron, the most stringent requirements on magnetic field quality at high fields come from the large amplitude orbits associated with resonant extraction. In this process the beam must be able to sustain amplitudes out to 25-27 mm for

Table 6: NEW TEVATRON PARAMETER LIST

	Tev A	Tev B*	Tev B**	
Circumference	6283	6283	6283	meters
Injection Energy	150	150	150	GeV
Peak Energy	1000	>1500	1500	GeV
Harmonic Number (@53 MHz)	1113	1113	1113	
Horizontal Tune	20.6	25.6	25.6	
Vertical Tune	20.6	25.6	25.6	
Transition Gamma	18.4	23.0	23.0	
Number of Bunches (Collider)	6-44	6-44	6-44	
Protons/Bunch	10	10	10	10^{10}
Antiprotons/Bunch	2-6	2-6	2-6	10^{10}
Transvèrse Emittance (Normalized)	12π	12π	12π	mm-mr
Longitudinal Emittance/Bunch	3.0	3.0	3.0	eV-sec
β^*	0.25	0.25	0.50	meters
β_{max}(Arcs)	100.0	100.0	100.0	meters
β_{max} (IR at Injection)	280.0	280.0	280.0	meters
β_{max} (IR at Low-β)	1650.0	1650.0	770.0	meters
Maximum Dispersion near IR	9	< 6	7	meters
Maximum Dispersion in arcs	5.8	2.5	2.5	meters
Number of Straight Sections	6	6	6	
Number of Possible IRs	2	3	3	
Length of Standard Cell	59.4	59.4	59.4	meters
Phase advance of Cell	68	90	90	degrees
RF Frequency	53.0	53.0	53.0	MHz
RF Voltage	1	1	1	MV
Number of dipoles in Standard Cell	8	6	8	
Dipole Field (Max)	4.4	>6.6	6.6	Tesla
Dipole Length (Standard)	6.1	8.1	6.1	meters
Cell Quadrupole Gradient (Max)	76	<140	148	T/m
Quadrupole Length (Standard)	1.7	1.7	1.7	meters
IR Quadrupole Strength (Max)	140	200	240	T/m

* Design goal

** Present design status

POLE	MEAN	RMS
Sextupole	0.95	3.12
Decapole	-0.57	1.32
14-pole	5.48	0.54
18-pole	-12.52	0.33
22-pole	3.70	0.26

Table 7: Present Tevatron Dipole Magnet Multipoles

half the circumference of the machine without any significant phase-space distortion due to higher order field harmonics in these magnets. The beam must be able to circulate for many turns at amplitudes of ≈ 20 mm. In view of the essential similarity of the beam dynamics, the design criteria for the magnetic multipoles for the dipoles are chosen to be those obtained from the measured Tevatron magnets. The dominant (allowed) multipoles in the Tevatron magnets as measured at 4000A in units of 10^{-4} at 1-inch are shown in Table 7.

The magnetic field quality at low excitation is defined by the large amplitude orbits associated with the proposed beam separation scheme for the collider operation. In order to avoid the luminosity limitation arising from the beam-beam interaction, electrostatic plates are used to create non- intersecting spiral closed orbits for the protons and antiprotons at the injection energy. The amplitude of these spiral orbits (± 7.5 mm) together with the relatively large beam size at the low energy require a "good field" region of ± 20 mm to permit adequate beam separation ($\geq 5\sigma$). The low field behavior of the magnets is complicated by the persistent current phenomena that produce systematic sextupole and decapole harmonics. It has been demonstrated that the present Tevatron magnets can sustain these large amplitude orbits, so again the existing machine provides guidance as to the necessary field quality. The orbit separation at collision energies (± 5 mm) provides less demanding field quality criteria than resonant extraction.

The design of a superconducting magnet is dominated by the characteristics of the superconducting cable. There are three important variables: temperature (T), magnetic field (B), and current density (J). For temperatures lower than the critical temperature there is a region of current density and magnetic field for which the superconductor exhibits zero resistance. The problem of magnet design is to ensure that no point in the magnet coil has combinations of J, B, and T that lie outside of the superconducting region. Other major design issues involve the coil geometry to provide the field shape, the size and shape of the iron yoke, and the containment of the mechanical stresses on the coil due to the Lorentz forces.

The cable design chosen for this magnet development is a hybrid of the two types of superconductor used at Fermilab: the Tevatron cable, and the low-beta cable currently in use in the new quadrupole construction for the interaction regions. The proposed cable will use 36 strands of superconductor similar to the low-beta cable, but each strand will be 0.681 mm in diameter like the Tevatron cable. The copper-to-superconductor ratio is chosen to be

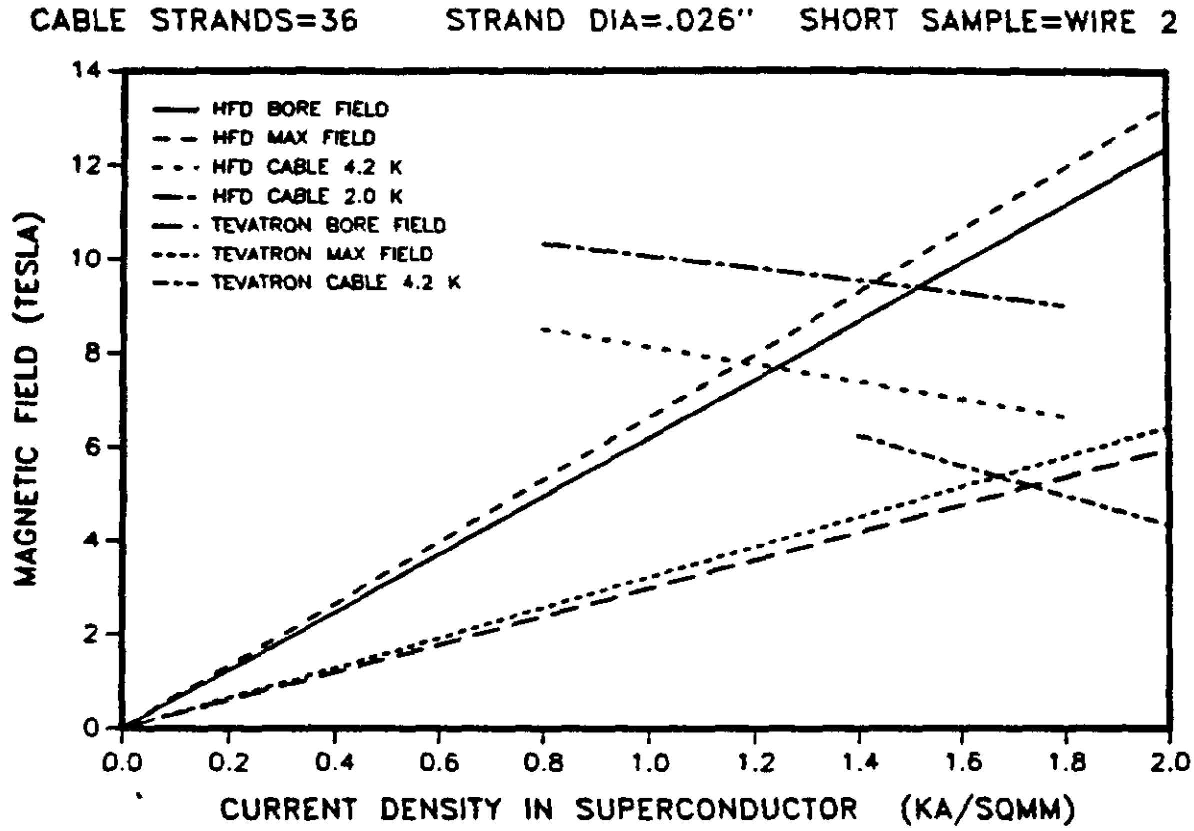

Figure 11: Estimated load line for cable used in New Tevatron magnets. Tevatron cable is shown for comparison.

1.5 to facilitate quench protection. This results in 5.24 mm^2 of superconductor in the cable. Recent measurements on the low-beta cable give a critical current density (J_c) of 1600-1800 A/mm^2 at 4.2 K and 7 T. Figure 11 shows the estimated load line for the superconducting cable at the two operating temperatures. The Tevatron cable is shown for comparison. There is a ~12% safety margin in cable performance above the required operating point.

The choice of filament size in the cable is important in minimizing the persistent currents and their time variation. These local current loops induced within the individual filaments give rise to systematic multipole fields in the magnets that diminish rapidly with increasing field. The dominant multipole is a sextupole although other allowed multipoles are present, e.g. decapole. Assuming full field penetration of the superconductor, the inherent magnetization at low excitation varies linearly with the filament diameter. The existing Tevatron magnets use a 9 μ filament diameter that results in a persistent current sextupole of 4 units at injection energy, or 120 units of chromaticity. A filament diameter of 6 μ has been specified for the new cable. Developments in cable fabrication techniques since the Tevatron have demonstrated that filament sizes of this order can be achieved. This would be expected to reduce the systematic sextupole at low field from the Tevatron levels, but would not remove this effect from operational significance.

Two recent developments in coil design techniques, wedges and offset placement, permit the construction of coils that generate better field quality than that achieved in the Tevatron. Conversely, small diameter coils (and hence smaller, less expensive magnets) can be used to generate the same field quality. Both of the techniques modify the current distribution in the cosine-theta style coils to more closely resemble the perfect current density distribution (no multipoles) which is a crescent shaped arrangement created by a pair of overlapping circles. The ability to design the perfect coil is limited by the cable size that introduces "granularity" into the process. The proposed coil cross-section uses both of these features.

The collared coil assembly is subjected to large azimuthal and radial magnetic forces that increase as the square of the central field and approximately linearly with coil diameter. The coil must be fully supported to resist motion to the highest excitation since coil motion gives rise to quenches and will also affect the field quality. The coils are subject to preload at the time of collaring which must be sufficient to ensure that the coils stay loaded throughout cooldown and powering. The main limitation to preload is turn-to-turn shorts in the coil as the insulation breaks down under pressure. Since the forces on the coil are independent of cable shape to first order, the pressure on the cable varies inversely with the cable width. A cable that is relatively wide has been chosen to make use of this behavior. Recent tests on Tevatron cable using Kapton insulation suggest that up to 20K psi of preload can safely be used. The largest forces demonstrated on a working magnet come from the HERA dipoles that have operated successfully with a 12.5K psi Lorentz force at a field of 6.9T.

The geometry of the iron flux return yoke is also a design issue. The closer the iron yoke is to the collared coil assembly, the larger the enhancement of the dipole field, and the magnet is more efficient. However, if the iron yoke is close enough so that saturation effects become significant, then a systematic sextupole moment is produced. This sextupole term increases with the onset of saturation and reaches a maximum value when approximately 2/3 of the inner iron surface is saturated. Inner iron geometries other than circular, e.g. elliptical, offer the possibility of increasing the iron distance from the coil at the point of saturation without removing the whole yoke to a greater distance. The outer dimensions of the iron yoke are also important since too little iron in the yoke will produce saturation at lower excitation. Oversizing the yoke to avoid these effects results in a bigger and more expensive magnet with a large amount of cold mass that increases the needed capacity of the cryogenic system. A tolerable level of sextupole at high fields involves questions of beam dynamics and the strength of the correction system. The present Tevatron correction sextupoles can correct up to 3 units of systematic sextupole in the dipoles at the highest energy.

A coil cross-section with the design features outlined previously is shown in Figure 12. The coil diameter is 70 mm, 6 mm less than the Tevatron magnets. The inner shell uses two wedges and the coil offset is 3.65 mm. This design achieves a field of 6.6T at a current of 5318A. The peak field in the coil windings is 7.4% greater than the dipole field which means that the magnet has a 10% safety margin, i.e. the estimated quenching threshold is 7.3T at 4.2 K. At 2 K the estimated peak field is 9.3 T. The circular iron yoke has an inner diameter of 186 mm and an outer diameter of 440 mm.

A calculated field profile from this design is shown in Figure 13, which gives the field deviation ($\Delta B/B$) across the aperture in units of 10^{-4}. Comparing with the similar data for the Tevatron magnet one can see that this coil deviates by less than one part in 10^4 across 92% of the coil aperture compared with the Tevatron dipole that obtains only 60% of the coil aperture as a good field region. The calculated multipoles in this magnet are indicated

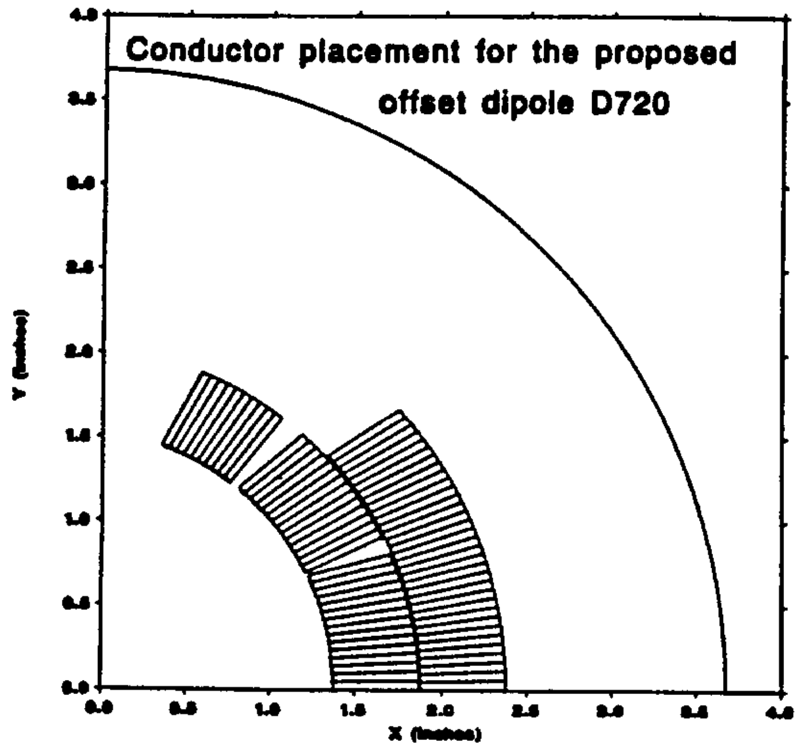

Figure 12: New Tevatron dipole magnet coil cross-section. Only one quadrant of the magnet is shown.

in Table 8. The fact that one can design a coil which produces such a large good field region means that the minimum coil diameter is not defined by the field quality criteria, but rather the physical aperture of the magnet. An analysis of the extraction process with large amplitude circulating particles and beam losses from the splitting septa striking the magnet bore tube leads to the conclusion that the necessary physical aperture of the magnets in the horizontal plane should be no smaller than the Tevatron diameter of 61 mm. A certain amount of space (2 mm) is necessary between the bore tube of the magnet and the coils to permit the flow of cryogens and to minimize the energy density deposited in the coils due to particles striking the beam pipe. These factors, together with the beam pipe thickness of 1.5 mm, define the inner coil diameter. The calculated forces on this coil give rise to a maximum pressure of 16 kpsi at 9T and 9 kpsi at 6.6T. Preload on the collared coil assembly must be sufficient to stabilize these forces on the coils, i.e., greater than 16 kpsi.

The high field (saturation) properties of this design are shown in Figure 14. The iron yoke dimensions were chosen so that saturation effects are negligible at 6.6T, and the systematic sextupole is less than two units up to 9T. The sextupole coefficient as a function of iron outer radius is shown in Figure 15. At the 9T excitation level the reduction in dipole field due to the saturation in the yoke is 3%. It is believed, however, that an elliptical iron yoke will improve this situation and that it should be possible to reduce the amount of iron somewhat.

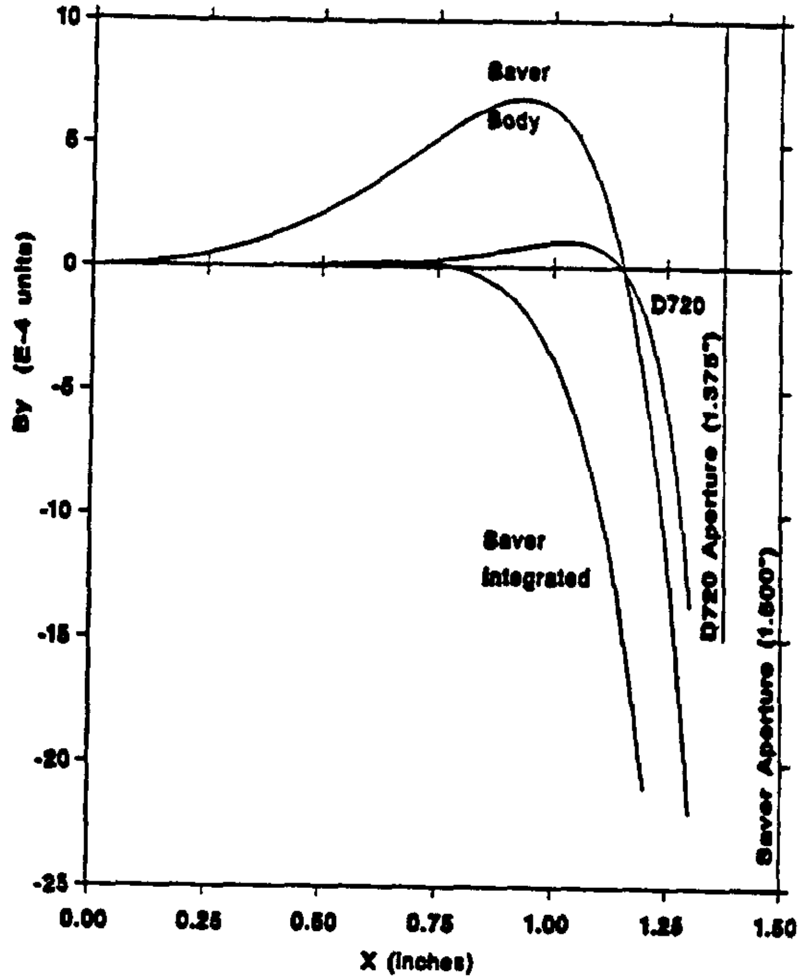

Figure 13: Field profile of the New Tevatron dipole magnet body. The field profile of the body of the present Tevatron dipole magnet, as well as its integrated field are also shown for comparison.

POLE	MEAN
Sextupole	0.00
Decapole	0.00
14-pole	1.45
18-pole	-0.49
22-pole	2.18
26-pole	-2.43

Table 8: New Tevatron Dipole Magnet Multipoles

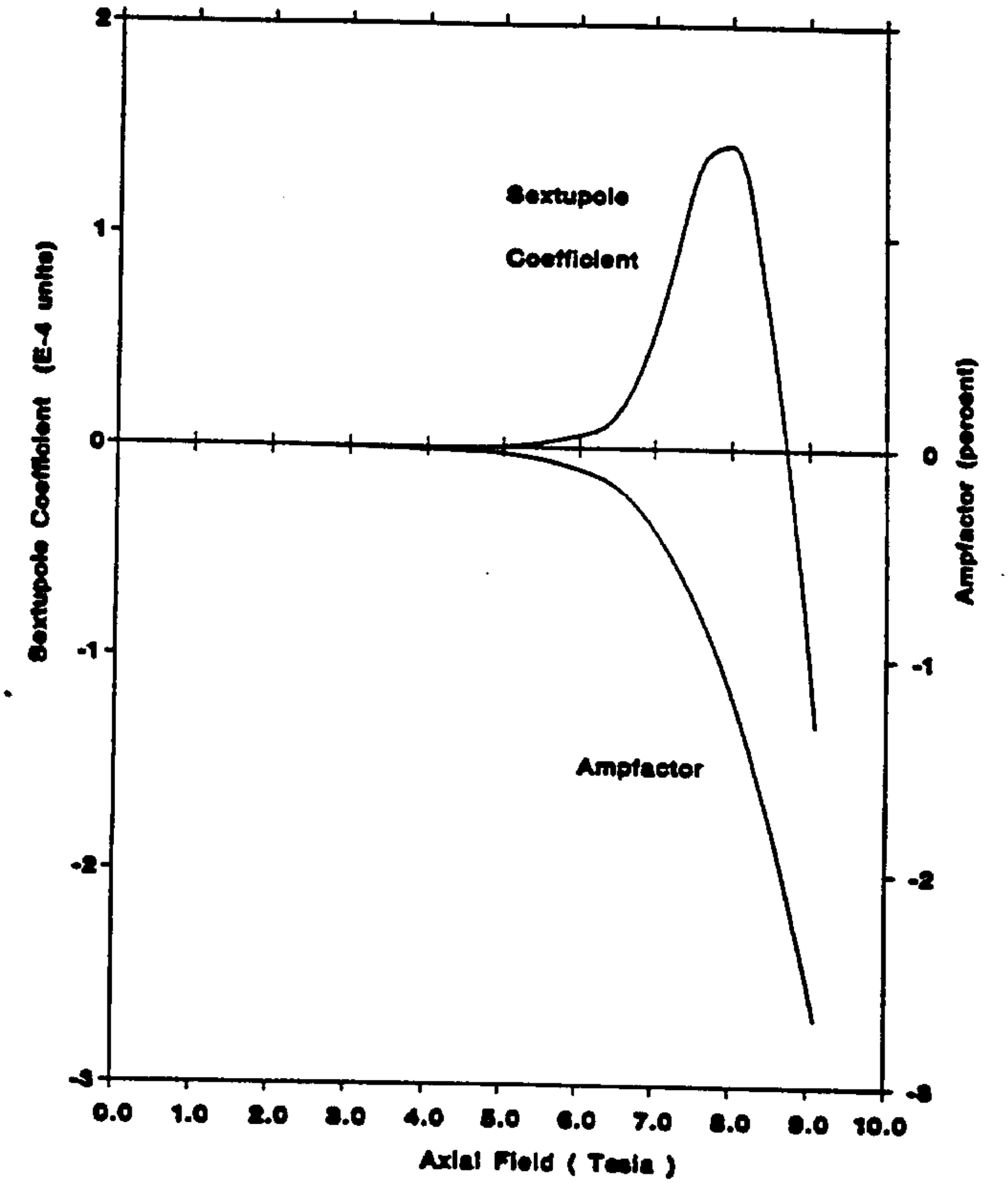

Figure 14: Saturation characteristics for New Tevatron dipole magnet. The sextupole coefficient appears on the left scale and the fractional deviation from a linear excitation function (ampfactor) appears on the right.

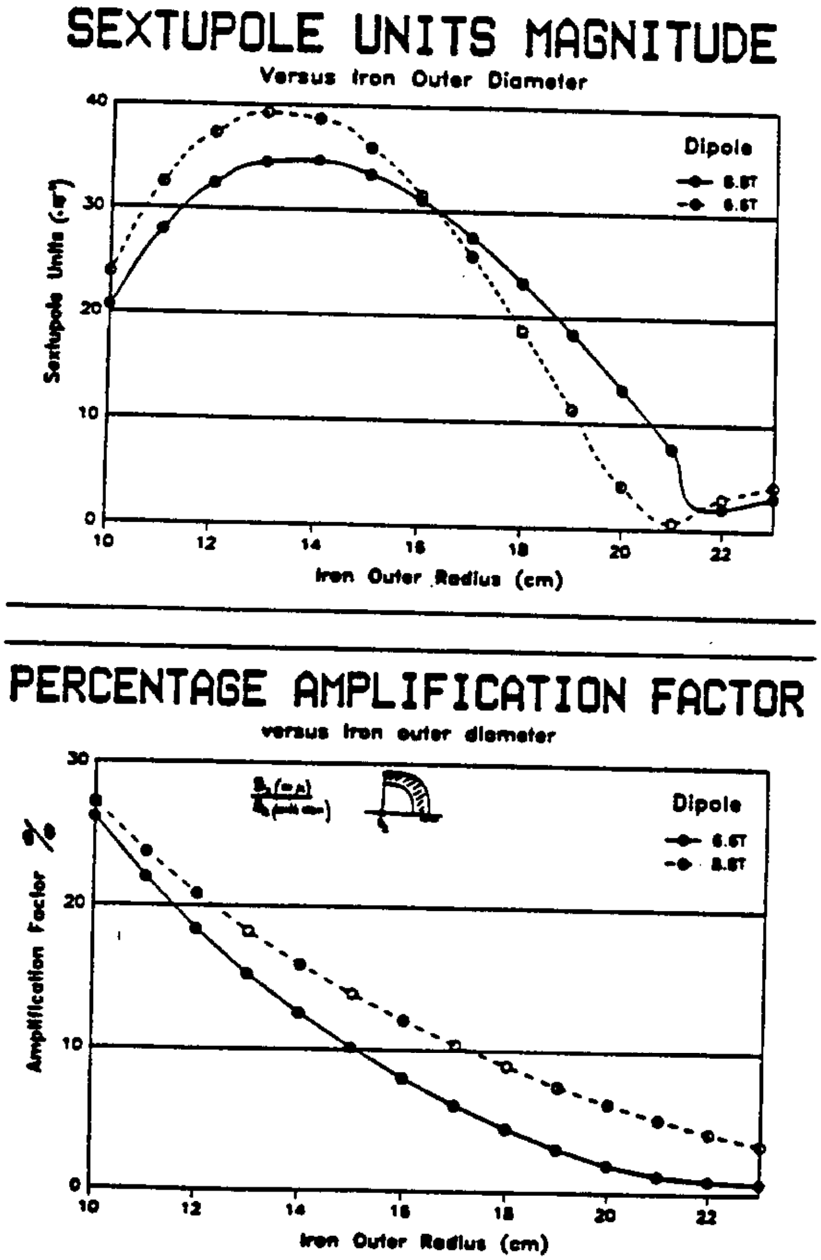

Figure 15: Sextupole coefficient and amplification factor as functions of iron outer radius at high field for the New Tevatron dipole magnet.

4.3 Benefits

Benefits expected from the construction of the New Tevatron include:

- Proton-antiproton collisions at center-of-mass energy in excess of 3.0 TeV and possibly as high as 3.6 TeV.
- Increase in luminosity by a factor of approximately 5/3 due to lower emittance at higher energy.
- Fixed target physics with primary protons at an energy of 1.5 TeV.
- Improved reliability in fixed target mode through the use of third generation superconducting magnets.
- The possibility of high luminosity proton-proton collisions at center-of-mass energy of 2.0 TeV is not excluded.

5 The Main Injector

5.1 Role of the Main Injector

The present bottleneck in the production of antiprotons and in the delivery of intense beams to the Tevatron is the Main Ring. The Main Ring is not capable of accelerating the quantity of beam which can be provided at injection by the 8 GeV Booster. This is for the simple reason that the admittance of the Main Ring ($12\pi/(\beta\gamma)$ mm-mr) is about half the size of of the Booster admittance ($20\pi/(\beta\gamma)$ mm-mr). [14] As a result the Booster is run at about two thirds of its capability during normal operations. The restricted aperture in the Main Ring is due to a combination of magnet field quality at low excitation and perturbations to the ring which have been required for the integration of overpasses and new injection and extraction systems related to operations with antiprotons.

The mismatch between Booster and Main Ring capabilities will become even more acute with the proposed 400 MeV linac upgrade, which is described in more detail in Section 6. This can be seen through examination of Figure 16 which shows how the Booster transverse emittance varies as a function of beam intensity. The emittance growth seen with increasing intensity is caused by the space charge forces encountered by the particles at the injection energy. By doubling the injection energy, these forces are reduced. The emittances are expected to follow the second curve in the figure. As well as the reduction in the space charge tune shift, the increased adiabatic damping of the betatron oscillations at the higher injection energy will make it possible to accelerate a beam with an emittance of 30π mm-mr in the Booster.

The construction of a new Main Injector synchrotron will allow the full utilization of the higher intensity proton beams which the Booster can deliver. Many other benefits can be derived from the construction of a new Main Injector as well. The colliding beams experiments are affected by the particle losses from the Main Ring during the antiproton production cycle. Because the charge of antiprotons in the Accumulator must be replenished shortly after a new store has been started in the Tevatron, the Main Ring operates continuously during Collider operation. At CDF where the Main Ring beam pipe both passes over the detector and is surrounded by 2 feet of iron, the losses in the vicinity of CDF are a significant source of background. At D0 the Main Ring beam will pass through the hadron calorimeter shielded only by the vacuum pipe. The potential for difficulty is much more severe. Some parts of the D0 detector may have to be turned off during the production cycle. At E0, where an elastic scattering experiment is in progress, the proportional chambers are damaged by the Main Ring losses and require repairs on a monthly basis.

[14] Admittance is defined as the transverse phase space area associated with a limiting half-aperture a at a point in the accelerator where the amplitude function is β; i.e., *admittance* $= \pi a^2/\beta$. To facilitate comparisons with normalized emittances, admittances will be expressed as a numerical factor multiplied by $\pi/(\beta\gamma)$, where when paired with the Lorentz factor in the parentheses, $\beta = v/c$ rather than the amplitude function.

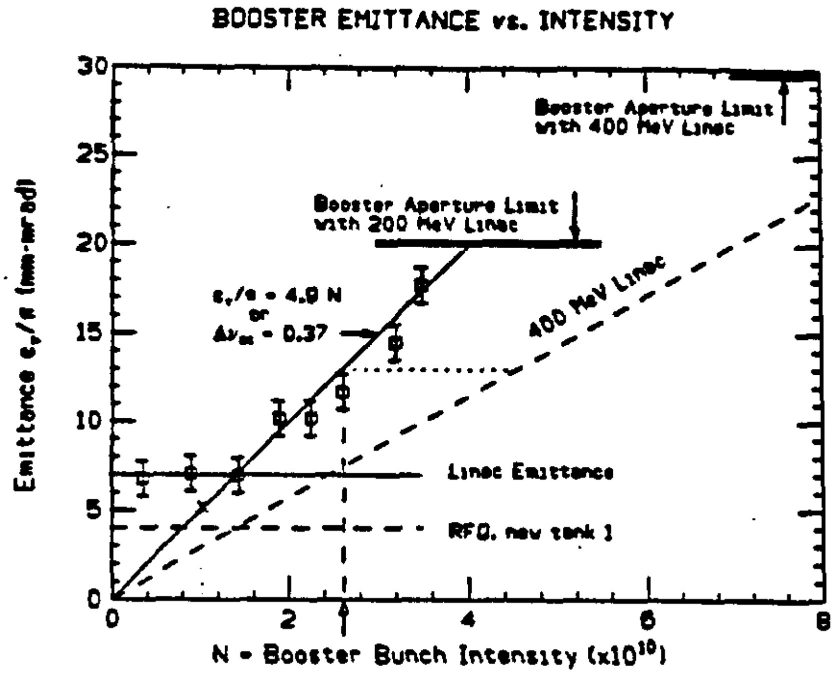

Figure 16: Booster emittance as a function of beam intensity.

The placement of the Main Injector outside of the Tevatron tunnel also allows for the year-round availability of lower energy fixed target beams to be used for experiments or for detector research and development. Resonant extraction, slow and fast, of high intensity proton beams must be used to provide the appropriate spill structure for this process, which is again a process that can produce background during colliding beams operation if the procedure were performed from the present Main Ring. The new injector in a separate tunnel would also allow for fixed target beams even when portions of the Tevatron tunnel are open for maintenance.

Another important reason for removing the injector from the present tunnel is to free up space for a future higher energy synchrotron. The Main Ring, after all, is a 150 GeV device residing in a space that could easily be occupied by a machine of more than 10 times that energy, using today's superconducting technology. Of course, this was the topic of discussion in the previous section. Whether the new superconducting synchrotron is built or not, however, the removal of the Main Ring from its present enclosure and the construction of the Main Injector is crucial to the goals of the Fermilab Upgrade.

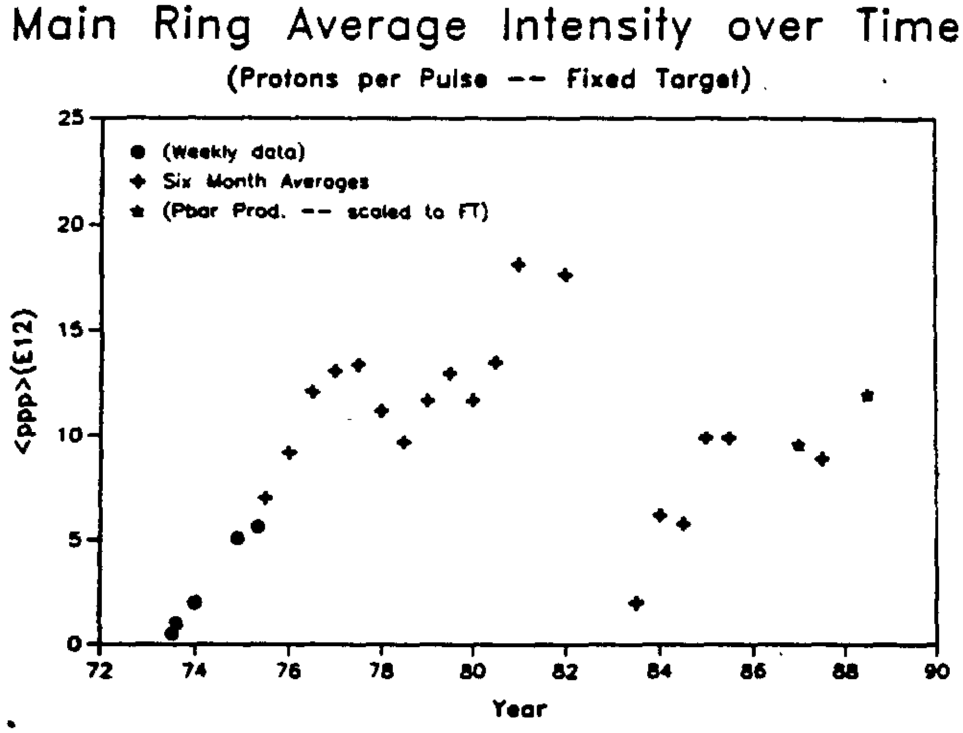

Figure 17: Main Ring average intensity over time. Peak intensities for periods of short duration are considerably larger, as noted in the text.

5.2 Evolution of the Main Ring and Its Problems

In mid-1981, the Fermilab Main Ring was operating as the world's highest energy and highest intensity proton synchrotron. For a few weeks the machine was routinely delivering 3×10^{13} protons per pulse to the fixed target experiments at an energy of 400 GeV. Figure 17 shows how the Main Ring's average fixed target intensity has developed over time. The points at the beginning of the plot are some typical weekly averages, while the rest of the points are averages over six months, beginning and ending on January 1 and July 1. The last and second to last points were gathered during collider operation when the Main Ring operates with one Booster batch injected instead of 13 for Main Ring fixed target operation or 12 in the Tevatron fixed target mode. These points have been scaled accordingly.

One sees immediately that the Main Ring has never fully recovered from the period of Tevatron installation during 1982-83. Since that time, even though the Main Ring operates now at less than 40% its previous energy, the single highest fixed target intensity has only been 1.8×10^{13} protons per pulse, set in late 1987.

The reasons for the decrease in intensity are difficult to single out. The Main Ring went through many changes since the dawn of the Tevatron era. Residual magnetic fields resulting from 120–150 GeV peak excitation are different from those associated with 400 GeV operation. While the original machine had a single injection point and a single extraction point, each with associated aperture restricting hardware, the "new" Main Ring was equipped with 5 such regions brought about by the need to inject and extract antiprotons as well as a new fast abort system (necessary when sharing the tunnel with a superconducting accelerator). Each of the septa used in these regions introduce some amount of nonlinear magnetic field to the machine; but more important, perhaps, is the fact that the low energy circulating beam must be steered around these obstacles in order to prevent beam loss. This steering requires the beam to pass far from the center of the neighboring dipole magnets, introducing even larger nonlinear fields. These undesirable fields may be contributing to the limitation of the dynamic aperture of the accelerator.

In addition, two vertical overpasses have been introduced into the Main Ring lattice in order to direct the circulating beam away from the center of the colliding beams detectors at B0 and D0. The B0 overpass introduces a large amount of vertical dispersion in the vicinity of the interaction region, but is cancelled at the two ends, leaving the rest of the accelerator unaffected. On the other hand, the D0 overpass was not as well matched to the accelerator lattice and hence results in a wave of vertical dispersion throughout the entire accelerator. This residual dispersion wave enlarges the vertical beam size where the dispersion is large, thus reducing the momentum aperture of the machine.

There have been attempts to improve the Main Ring performance over the past several years. For instance, a new 8 GeV Line was built to allow for greater efficiency of beam transfers between the Booster and Main Ring without being susceptible to emittance dilution. Improvements to the D0 overpass have resulted in a lower dispersion wave, a much better emittance match to the Tevatron at transfer, and may be part of the reason for the slight increase in Main Ring performance in recent months. Magnets of questionable aperture in specific locations around the ring have been replaced by larger aperture magnets. None of these have directly accounted for the one-third reduction in intensity.

Recent studies have been performed, and are continuing to be performed, to attempt to understand the source of the beam loss in the Main Ring at injection. Figure 18 shows a typical Main Ring pulse where the time spent at the injection energy of 8.9 GeV is on the order of 0.5 sec. The lower curve is the Main Ring bend magnet current vs. time. The beam loss which appears immediately upon injection disappears after the beam has reached an energy of roughly 20 GeV. (It was this observation that lead to a feasibility study for a 20 GeV booster synchrotron.) Machine studies conducted in late 1987 indicated that the beam lifetime at 8.9 GeV was on the order of 5 sec., while beam that was accelerated to 20 GeV and allowed to coast there for a few seconds had an initial lifetime of more than 600 seconds. By inducing betatron oscillations at 20 GeV using a pulsed kicker magnet, the machine admittance was measured as $40\pi/(\beta\gamma)$ mm-mr, while the admittance at 8.9 GeV was $12\pi/(\beta\gamma)$ mm-mr. The factor of three increase in admittance is greater than that expected due to adiabatic damping alone.

Meanwhile, magnetic measurements of 38 Main Ring dipole magnets had been performed at several excitation currents. The results indicated that the harmonic content, especially the sextupole terms, were much worse at the injection field than at higher excitations. Numerical tracking results using a distribution based upon the measured field harmonics at 8 GeV have yielded cases whereby a particle may experience what appears to be stable motion for thousands of turns, then suddenly its amplitude will grow until the particle is lost from the machine. This type of behavior is depicted in Figure 19. In this figure, the horizontal

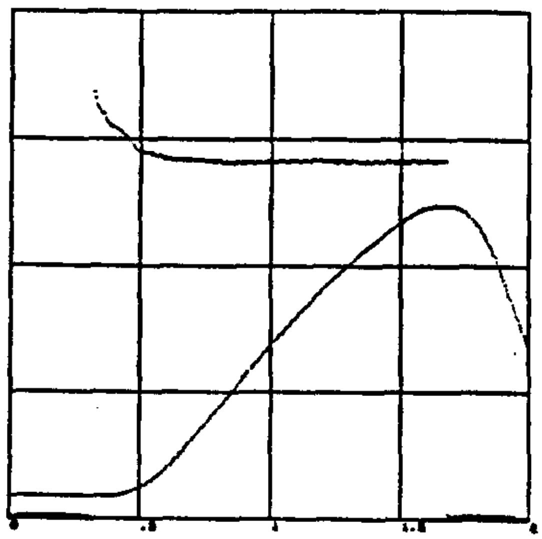

Figure 18: Main Ring intensity vs. time during cycle. The upper curve is the beam current while the lower curve is the magnet current during 120 GeV antiproton production cycle.

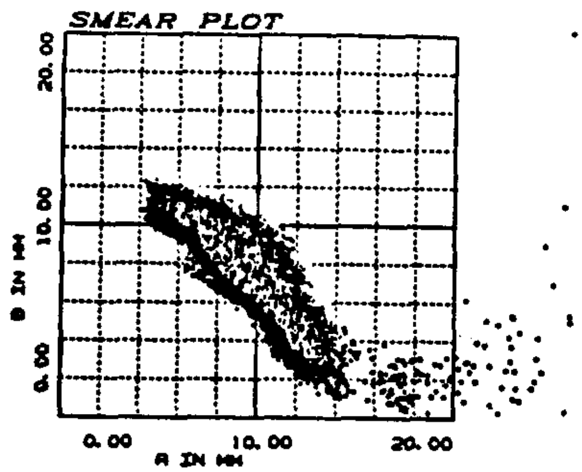

Figure 19: Particle tracking result at 8 GeV.

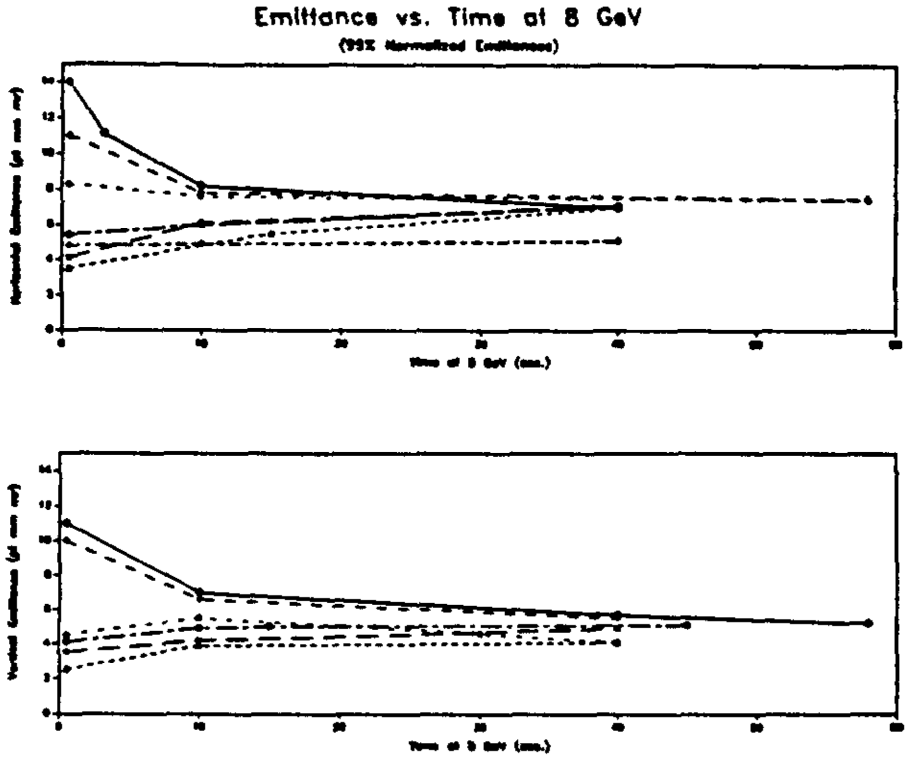

Figure 20: Main Ring emittance vs. time spent at 8 GeV.

and vertical axes are the horizontal and vertical betatron oscillation amplitudes respectively. Linear, uncoupled behavior would result in a point when plotted for many turns. For this particular plot, the starting particle remained in the wide band for approximately 33,000 turns after which time the horizontal amplitude began to grow rapidly.

In order to produce the behavior seen in the above figure, the numerical model needed to include both systematic and random field errors, as well as closed orbit offsets and synchrotron motion of an off-momentum particle. The closed orbit offsets used are those found in the real Main Ring, which are primarily due to the orbit bumps around the magnetic septa discussed above. The particle momentum used for this run was 1.5 times the rms particle momentum typically found in the Main Ring beam upon injection.

Magnetic field measurements at an excitation corresponding to 15 GeV have also been performed. These results are now being used to compare the expected particle behavior at this energy with the behavior at 8 GeV. Beam measurements at these two energies using small transverse emittance and small momentum spread beams are soon to be carried out.

The Main Ring admittance of $12\pi/(\beta\gamma)$ quoted earlier reflects the maximum beam size that survives circulation in the Main Ring for the short time (typically less than one second) prior to acceleration. Studies that have been performed thus far indicate that the equilibrium admittance of the Main Ring is on the order of $5 - 7\pi/(\beta\gamma)$ mm mr. Beams of variable incoming emittance have been injected into the Main Ring at 8.9 GeV and allowed to coast for up to 60 sec. at that energy. The results of one such set of measurements is shown in Figure 20. What is plotted is the emittance as derived from the variance of the transverse beam distribution according to

$$\epsilon = \frac{6\pi\sigma^2}{\beta} \times \gamma.$$

For large incoming emittances, the emittance decreases with time until equilibrium is reached. For small incoming emittances, the emittance grows toward equilibrium. This behavior is understandable in terms of a diffusion process in the presence of a hard aperture. The hard aperture may be either a physical aperture or it may be a dynamic aperture for which the particles are lost in a short time scale compared with the lifetime caused by the diffusion process.

At equilibrium, the beam intensity lifetime, τ, and the average rate of individual particle emittance growth, D, are related to the equilibrium admittance, $\hat{W}$, by

$$\tau = 1.45\frac{\hat{W}}{D}.$$

The diffusion rate D deduced from measurements of lifetime and emittance at equilibrium is consistent with multiple Coulomb scattering off of the residual gas.

The observation that the lifetime and equilibrium admittance both increase when the RF accelerating cavities are turned off confirms that the aperture is dynamic rather than physical. This also points out that momentum plays a crucial role in determining a particle's fate in the Main Ring environment. Future numerical tracking and experimental measurements will focus on this aspect. It is hoped that the results from these studies will help to develop an acceptable aperture criterion for the new Main Injector to ensure better performance than the present Main Ring.

5.3 Outline of Design

The Main Injector (MI) is to be located south of the Antiproton Source and tangent to the Tevatron ring at the F0 straight section as shown in Figure 21. The MI will perform all duties currently required of the existing Main Ring. Thus, following commissioning of the MI, the background in the colliding beam detectors caused by the Main Ring will be eliminated. The performance of the MI, as measured in terms of total protons delivered to the Tevatron, is expected to exceed that of the present Main Ring operation by a factor up to three (assuming that the linac upgrade has already taken place). The proton flux delivered by the MI to the antiproton production target could increase by as much as a factor of five above present rates from the Main Ring. In addition the MI will provide high duty factor 120 GeV beam to the experimental areas during collider operation–a capability which does not exist in the Main Ring.

The location, operating energy, and mode of construction of the Main Injector is chosen to minimize operational impact on Fermilab's ongoing High Energy Physics (HEP) program. The area in which the MI is to be situated is devoid of any underground utilities which might be disturbed during construction, while the separation between the MI and Tevatron is sufficient to allow most of the construction during Tevatron operations. The energy capability of the MI is chosen to match the antiproton production and Tevatron injection energies presently used in the Fermilab complex.

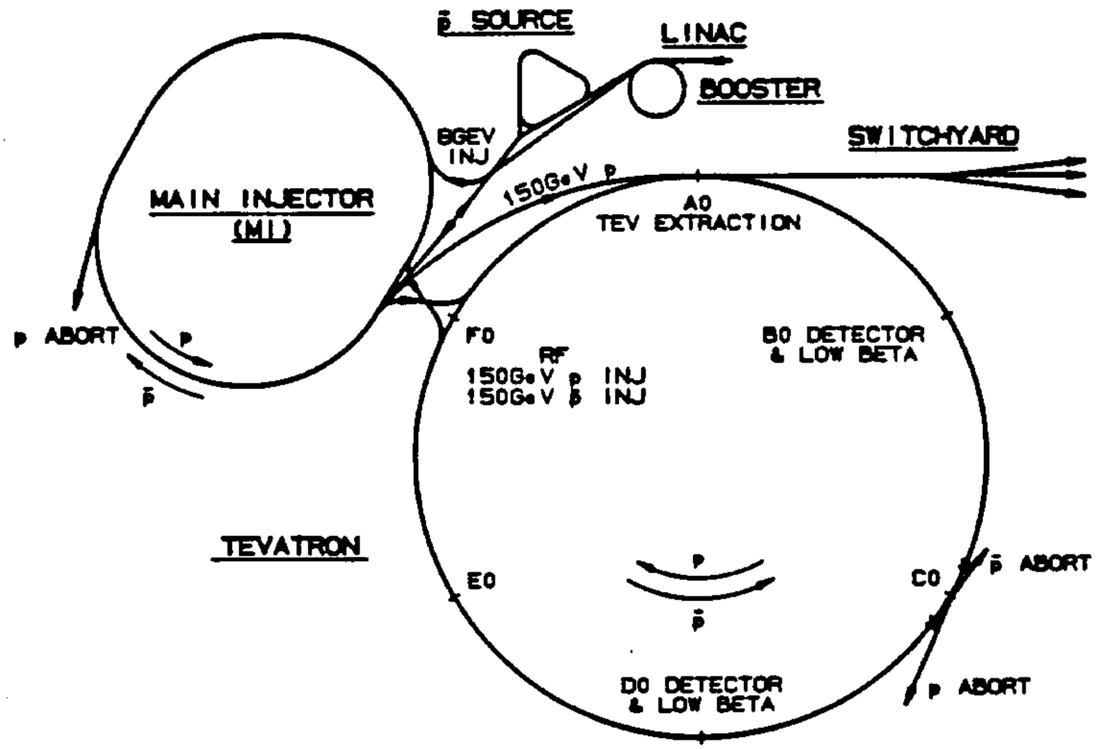

Figure 21: Fermilab Tevatron accelerator with Main Injector.

The Main Injector will be built from newly constructed dipole magnets allowing a large portion of the installation process to proceed independently of Tevatron operations. The Main Ring dipoles have a very poor record of reliability. During the period 1975 to 1982 when 400 GeV was the standard operating energy there were 141 dipoles removed either because of a failure or because there was evidence that the magnet insulation had deteriorated. Since 1983, when the nominal operating energy was reduced to 150 GeV, 30 dipoles have been removed for this reason. Since the Main Ring was built, Fermilab has built a large number of magnets that have been free of failures. For example none of the nearly one thousand magnets that were built for the Antiproton Source have failed although they have been in continuous use since early 1985. The dipoles for the Main Injector should be very reliable because they will have an insulation system based on the success of the past ten years of conventional magnet development at Fermilab. The use of newly designed dipoles is also desirable from the standpoint of power usage for antiproton production as is discussed below.

The Main Injector ring and all beamline interconnections to existing facilities are shown schematically in Figure 21. It is proposed to complete construction over a four and one-half year period starting on October 1, 1990. This construction duration is chosen to mesh with the schedule for production of New Tevatron magnets, in order to use a single shutdown period for installation of both new rings. It is anticipated that the construction and operation of the new Main Injector will not require any expansion of the Fermilab permanent staff.

The Main Injector parameter list is given in Table 9. It is anticipated that the Main Injector will perform at a significantly higher level than the existing Main Ring as measured

Table 9: Main Injector Parameter List

Circumference	3319.419	meters
Injection Energy	8.9	GeV
Peak Energy	150	GeV
Minimum Cycle Time (@120 GeV)	1.5	sec
Number of Protons	3×10^{13}	
Harmonic Number (@53 MHz)	588	
Horizontal Tune	22.42	
Vertical Tune	22.43	
Transition Gamma	20.4	
Natural Chromaticity (H)	-27.5	
Natural Chromaticity (V)	-28.5	
Number of Bunches	498	
Protons/bunch	6×10^{10}	
Transverse Emittance (Normalized)	25π	mm-mr
Longitudinal Emittance	.25	eV-sec
Transverse Acceptance (at 8.9 GeV)	$40\pi/(\beta\gamma)$	mm-mr
Momentum Acceptance	2.0	%
β_{max} (Arcs)	57	meters
β_{max} (Straights)	80	meters
Maximum Disperion	2.2	meters
Number of Straight Sections	8	
Length of Standard Cell	34.3	meters
Phase Advance per Cell	90	degrees
RF Frequency (Injection)	52.8	MHz
RF Frequency (Extraction)	53.1	MHz
RF Voltage	4	MV
Number of Dipoles	300	
Dipole Length	6.1	meters
Dipole Field (@150 GeV)	17.2	kGauss
Number of Quadrupoles	202	
Quadrupole Gradient	196	kG/m
Number of Quadrupole Types	3	
Number of Quadrupole Busses	2	

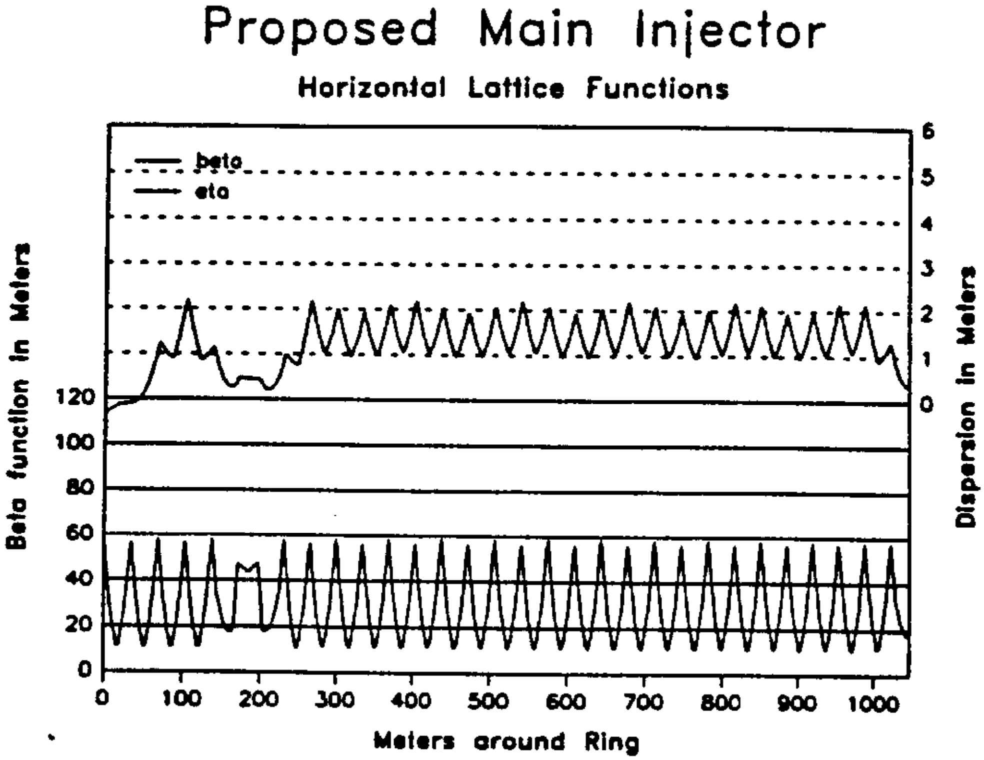

Figure 22: Main Injector horizontal lattice functions. The upper curve is the dispersion function, the lower curve the amplitude function. Only one third of the ring's circumference is shown here.

either in terms of protons delivered per cycle, protons delivered per second, transmission efficiency, or reliability. For the most part expected improvements in performance are directly related to optics of the ring. The lattice functions of the MI are shown in Figure 22. The MI ring lies in a plane with stronger focussing per unit length than the Main Ring. This means that the maximum betas are half as big and the maximum (horizontal) dispersion a third as big as in the Main Ring, while vertical dispersion is nonexistent. As a result physical beam sizes associated with given transverse and longitudinal emittances are significantly reduced compared to the Main Ring. The elimination of dispersion in the RF regions, raising the level of the injection field, elimination of sagitta, and improved field quality in the dipoles will all have a beneficial impact on beam dynamics.

The Main Injector is seven times the circumference of the Booster and slightly more than half the circumference of the existing Main Ring and Tevatron. Six Booster cycles will be required to fill the MI and two MI cycles to fill the Tevatron. The MI is designed to have a transverse aperture of $40\pi/(\beta\gamma)$ mm-mr (both planes). This is 30% larger than the expected Booster aperture following the 400 MeV linac upgrade, and a factor of four larger than that of the existing Main Ring. It is expected that the linac upgrade will yield a beam intensity out of the Booster of $5\text{–}7\times10^{12}$ protons per batch with a $20\text{–}30\pi$ mm-mr transverse and a 0.25 eV-sec longitudinal emittance. A single Booster batch needs to be accelerated for antiproton production while six such batches are required to fill the Main

Injector. The MI should be capable of accepting and accelerating these protons without significant beam loss or degradation of beam quality. Yields out of the Main Injector for a full ring could be potentially as great as 5×10^{12} in a single batch and 3×10^{13} protons in six batches (6×10^{13} injected into the Tevatron.) By way of contrast the existing Main Ring is capable of accelerating 1.8×10^{12} protons in a single batch and 1.8×10^{13} protons in twelve batches for delivery to the antiproton production target and the Tevatron respectively.

The power supply and magnet system are designed to allow a significant increase in the number of 120 GeV acceleration cycles which can be run each hour for antiproton production, as well as to enable us to run a 120 GeV slow spill with a 35–50% duty factor. The cycle time at 120 GeV can be as low as 1.5 seconds for antiproton production. This is believed to represent the maximum rate at which the Antiproton Source might ultimately stack antiprotons and is to be compared to the current Main Ring capability of 2.6 seconds. The slow spill capability of the Main Injector is not presently duplicated in the existing Main Ring. The dipole magnets to be used are designed with twice the total cross section of copper and half as many turns as existing Main Ring dipoles. This is done to keep the total power dissipated in the ring during antiproton production at roughly the same level as in present operations while keeping the number of power supplies and service buildings low.

At least four distinct roles for the MI have been identified along with four corresponding acceleration cycles. These are identified in Table 10 along with the average power over the cycle for each case. For reference the present 120 GeV antiproton production cycle runs at

Table 10: Main Injector Operations Scenarios

Operational Mode	Energy		Cycle		Flattop		Power	
Antiproton Production	120	GeV	1.5	sec	.05	sec	7.1	MW
Fixed Target Injection	150		3.0		.05		6.2	
Collider Injection	150		9.0		3.0		10.9	
High Intensity Slow Spill	120		2.9		1.0		11.9	

2.6 seconds and 4.3 MW.

In the antiproton production mode a single Booster batch containing 5×10^{12} protons is injected into the Main Injector at 8.9 GeV/c. These protons are accelerated to 120 GeV and extracted in a single turn for delivery to the antiproton production target. As mentioned elsewhere it is anticipated that with this flux of protons onto the target and expected improvements in the Antiproton Source the antiproton production rate will exceed 1×10^{11}/hour.

For fixed target injection the MI is filled with 6 Booster batches each containing 5×10^{12} protons at 8.9 GeV/c. Since the Booster cycles at 15 Hz, 0.4 seconds are required to fill the MI. The beam is accelerated to 150 GeV and extracted in a single turn for delivery to the Tevatron. The MI is capable of cycling to 150 GeV every 3 seconds. Two MI cycles are required to fill the Tevatron at 150 GeV.

The MI operates on a 9 second, 150 GeV cycle for delivery of beam to the Tevatron for collider operations. The acceleration cycle and beam manipulations are the same for both protons and antiprotons. A 3 second flattop is required for bunch coalescing and cogging of the beams prior to injection into the Tevatron. Though the sequence of loading the Tevatron is not fully defined at this point, it is expected that the number of Main Injector cycles required to load both protons and antiprotons will not be greater than sixteen to eighteen. This results in an 3 minute collider fill time.

A much higher intensity, high duty factor (34%) beam can be delivered at 120 GeV with a 2.9 second cycle time for experimental programs such as kaon decay physics. The average current delivered is about 2 μA (3×10^{13} protons/2.9 sec.) and debunched beam without radiofrequency structure would be required. Running in this mode does not put any peak demands on the power supply system beyond those imposed by the antiproton production cycle, but it does expend twice the average power. This cycle can also be used to provide test beams to the experimental areas during collider running. In this mode it is likely that a much lower duty factor, accompanied by a much lower average power, would satisfy experimenters' test needs.

Combinations of the above operational modes are also possible. One such example is simultaneous operation for antiproton production and high intensity slow spill. One might load the MI with six Booster batches containing 3×10^{13} protons, accelerate to 120 GeV, fast extract one batch to the antiproton production target, and slow extract the remainder of the beam over a second. This would produce slightly more than half the antiproton flux and 83% of the average intensity of the first and last scenarios listed in Table 10.

5.4 Benefits

Benefits expected from the construction of the Main Injector include:

- An increase in the number of protons targeted for $\bar{p}$ production from 5×10^{15}/hour (following the linac upgrade) to 1.2×10^{16}/hour.
- A potential increase in the number of protons delivered to the Tevatron to 6×10^{13}.
- Improvement in large-stack antiproton transfer efficiency of 10 to 20% due to large Main Injector admittance.
- The reduction of backgrounds and deadtime at the CDF and D0 detectors through removal of the Main Ring from the Tevatron enclosure.
- Provision for slow extracted test and commissioning beams at >100 GeV during collider operations.
- Freeing up the E0 Tevatron straight section for possible use as a third interaction region by moving beam tranfers to F0.
- The creation of space in the Tevatron enclosure for eventual installation of a second superconducting accelerator.

- The potential for development of very high intensity, high duty factor ($\approx 10^{13}$ protons/sec at 120 GeV with a 34% duty factor) beams for use in high statistics K decay and neutrino experiments.

It is expected that with the construction of the Main Injector and the completion of planned improvements to the Antiproton Source the antiproton production rate will exceed $1 \times 10^{11} \bar{p}$/hour, and that a luminosity in excess of $2 \times 10^{31} cm^{-2} sec^{-1}$ will be supportable in the existing collider.

6 The Present Phase

In the near term (1990-92), there are a number of programs underway to increase the luminosity to the 1/3 to 1 $\times 10^{31} cm^{-2} sec^{-1}$ range. Work discussed here feeds naturally into the requirements of Phases II and III. In some sense it provides the glue or infrastructure that will allow for the larger projects to be effective. For instance, the integrated approach for increasing antiproton production begins in the near term and develops further as the Main Injector becomes available.

Two aspects of the first phase which are essential to future developments are the successful implementation of the separator scheme in the Tevatron and the ability to push stack intensity limits and stacking rate as a function of stack size in the Antiproton Source.

6.1 Interaction Region Optics

In the Tevatron, near term activities are directed toward the installation of a low-β focusing system at the D0 interaction region and a new replacement system at the B0 interaction region. The design which has been developed differs from that installed at B0 now in that it is a matched system in both transverse betatron space and in momentum dispersion. Thus, the two interaction regions and their adjustment are independent. This solution could equally well be implemented at any number of straight sections, whereas the original B0 solution did not allow for the addition of IR's and required injection into the normal fixed target lattice optics, and then a continuous tuning from fixed target to low-β optics once flattop was reached.

The new low-β system should allow for β^*'s as low as 1/4 m at quadrupole gradients of 1.4 T/cm (as compared with 1 T/cm for the present B0 system and 3/4 T/cm for the standard Tevatron lattice quads). The present B0 low-β operates at $\beta^* = 0.55$ m.

The completely matched lattice solution unfortunately requires a number of independently controlled quadrupoles, 18 per IR as opposed to 10 for the present B0. There will be 11 independent power supplies per IR vs. 4 at present. All of this represents considerable cryogenic complexity and a substantial increase in the number of cryogenic power leads required.

Many of the elements are distributed back in the lattice, up to six half-cells away from the IR. For these locations a new single-shell quad has been developed that utilizes a so called 5-in-1 conductor. Cable is made of five individually insulated conductors, and after the coil is wound the individual conductors are spliced in series. In this coil gradients of 1 T/cm are possible at currents of 1.6 KA.

The two-shell quad uses 36 strand cable with a 0.0208 inch strand diameter. This makes a very thin aspect ratio cable in order to reduce the maximum operating current and thus the current lead cryogenic load and warm buss requirements. Gradients of 1.4 T/cm are achieved at 4.8 KA.

Both magnets have an inside coil diameter of 3 inches and use conductor with a demanding strand superconductor specification of 3000 A/mm^2 at 4.2° and 5 T. Strand has been obtained that has better J_c characteristics than SSC strand and meets these requirements.

6.2 Separated Beams

A critical feature of the upgraded proton-antiproton collider is the ability to operate with separated beams so that collisions occur only at the detector interaction regions. At present luminosity performance is limited by the beam-beam tune shift given approximately by

$$\Delta\nu = 0.007 \times (hits/rev.) \times \frac{N(10^{10})}{\epsilon_N(10^{-6})} \leq 0.02.$$

In the long run, the best way to overcome this limitation is to have the protons and antiprotons on different orbits spiraling about one another and brought into collision only at the desired detector interaction regions, instead of having them follow the same identical orbit around the whole accelerator and collide with each other at every crossing point.

In the Tevatron separated beams will be obtained using electrostatic separators to deflect the protons and antiprotons on two distorted orbits. Using both horizontal and vertical separators spaced 90° apart in the betatron phase advances, it is possible to obtain a corkscrew - double helical motion of the counterrotating proton and antiproton beams.

In order to implement this, closed orbit bumps are produced in each plane between downstream B0 and upstream D0, and then between downstream D0 and upstream B0. The orbit oscillations are initiated by separators located just outboard of the low β quad triplets on either side of the interaction regions. Closure of each orbit bump is obtained by a third "middle" element located in an intermediate warm space between the two IR's at locations B48, C17, F0 and F17. (It is the need for these third orbit closing elements which makes it appear difficult to implement IR's in adjacent straight sections, for there just is not sufficient warm space between two adjacent straight sections to locate these third elements at the appropriate relative phase.) In total there are 23 3-meter modules required. Operating voltages are typically 35 kV/cm over a 5 cm gap. Higher gradients up to 50 kV/cm are required for short periods of time during injection and acceleration. Figure 23 shows the horizontal and vertical orbit distortions around the ring for one beam that is required during collisions at 1000 GeV in order to obtain the appropriate helix.

The total amount of beam separation (one beam to other) specified in the design is 5σ based upon experience at the CERN Sp$\bar{p}$S. The most demanding requirements are at injection and low energy where the beam size is large due to both transverse size and momentum spread in the relatively high dispersion lattice of the Tevatron. (A new Tevatron design as described earlier in this document could compensate for this shortcoming.) Beam separations of 15 mm are required and the beams use up much of the good field magnetic aperture. Accelerator studies are in progress to determine that single beams (i.e. protons) can be stored and manipulated with these large orbit distortions without deterioration. The studies are also used in order to determine the necessary differential corrector strengths required between the proton and antiproton beams in order to correct any differences in their tune, coupling, chromaticity, etc. caused by double helix nature of the two orbits.

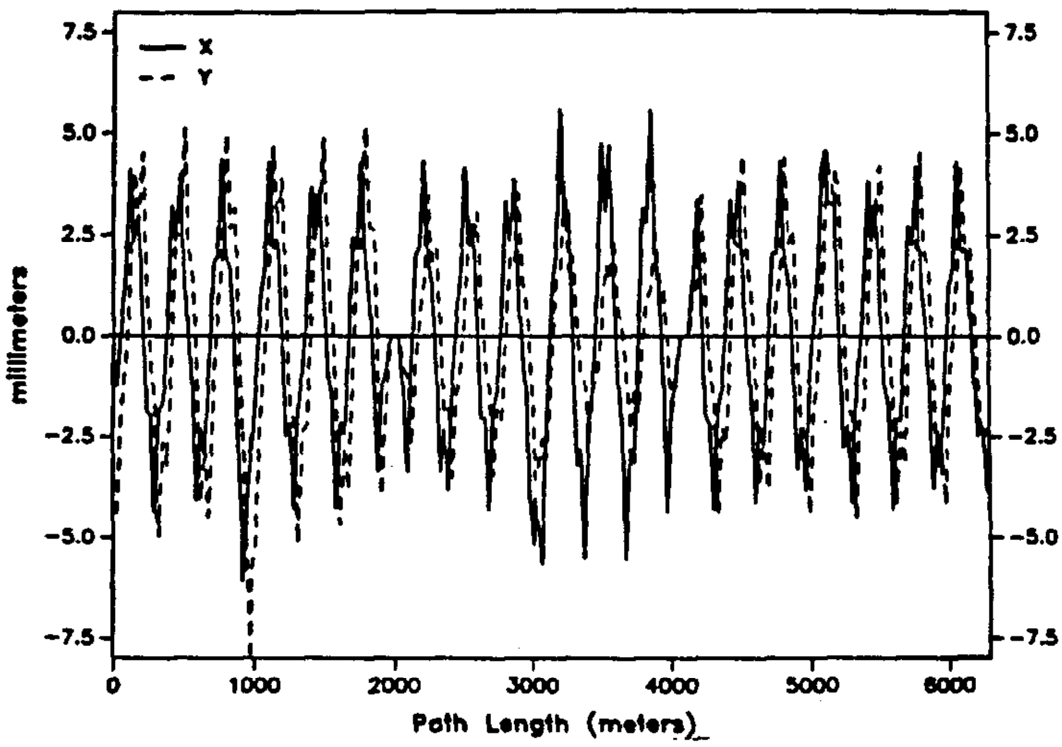

Figure 23: Distortion of closed orbit for one beam required to obtain helical separation of beams during collisions at 1 TeV.

An additional consideration that is being addressed by computational methods is the so called long-range, beam-beam tune shift caused by two beams passing each other at a distance. Arriving at conclusive results here is difficult as in many other aperture type questions.

The separator program as outlined here is ambitious and may not be completely successful. Only experience will tell us how far we really can push and still achieve reliable operation. In contrast to the above outline which requires 23 units operating at 35 kV/cm and helical separation in two dimensions, CERN presently uses a horizontal separation scheme that requires three units operating at 20 kV/cm.

6.3 Improvements to Antiproton Source

In order to provide for a sufficient number of antiprotons for increased luminosity in collider operation, both the maximum stack size limit and the stacking rate must be increased. Thus, there are three parameters which must be addressed; a), stack size limit, including beam instability limits; b), antiproton production per proton on target; and c), protons on target per second. The upper plot in Figure 24 shows the present stacking rate per proton. Table 1 indicates that stacks of the order of 130×10^{10} antiprotons and stacking rates of the order of 10^{11} antiprotons/hr are required by the time Phase III is realized. The goal is

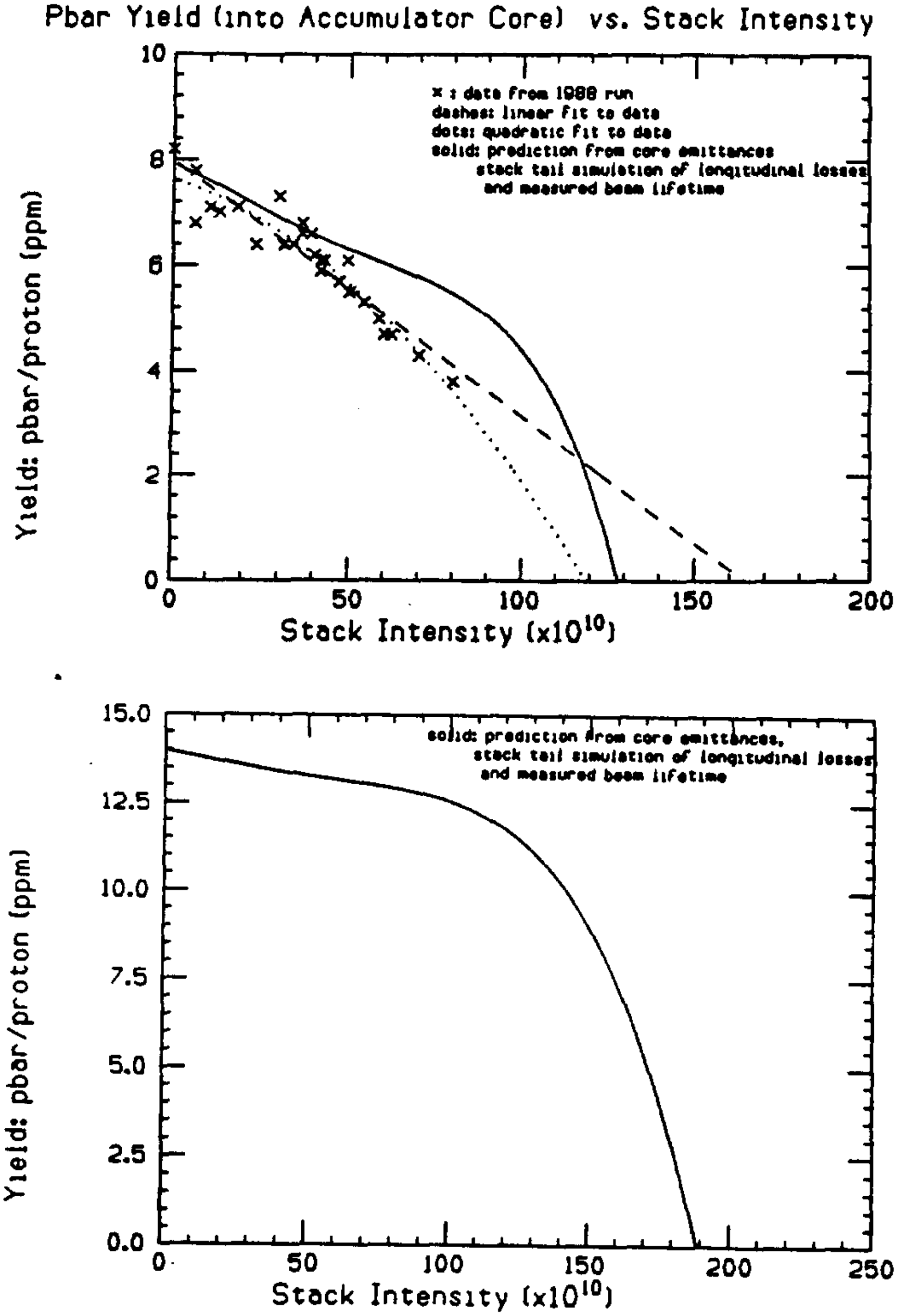

Figure 24: The upper plot compares present experience and prediction regarding antiproton yield versus stack size. The lower plot shows the predicted yield vs. stack size following the increased flux and improvements to the core cooling system expected in Phase I of the Upgrade.

to improve the antiproton yield per proton by a factor of 2, and the number of protons on target per second by a factor of more than four, to give a peak stacking rate of 14×10^{10} antiprotons per hour. As the targetting cycle time and collection efficiency are improved, improved performance of the cooling systems will also be required to handle the increased flux and repetition rate.

Figure 24 shows a predicted decrease in stacking rate vs stack intensity. This predicted decrease is due to three loss mechanisms which grow with stack intensity:

1. beam loss due to interaction with the Accumulator residual gas (300 hour lifetime);

2. longitudinal beam loss from the stack tail and core due to limitations in the stochastic stacking system, which results in beam loss when the beam hits the edges of the machine momentum apertures;

3. transverse beam loss from the core, due to the growth of the transverse emittance with stack intensity (approximately linear) and the consequent beam loss when the beam hits the edges of the machine transverse apertures.

As indicated in the upper graph, present data show a considerably more rapid reduction with stack size than the prediction. Operationally, it is found that to maintain stability in the stochastic stacking system, as the stack size grows above $40 - 50 \times 10^{10}$, it is necessary to reduce the gain of the stack tail system, resulting in larger longitudinal losses than predicted for the ideal system. It is believed that this tendency of the system to become unstable is caused by extraneous microwave power picked up in the stack tail system from the core beam. Presently a cure for this is underway and consists of installing ferrite absorbers to damp the microwave power. Results should be known in a few months.

The stack size end point limit shown in the prediction in Figure 24 corresponds to the point at which the input stack flux equals the loss due to the three mechanisms described above. A higher frequency core cooling system is being developed; this will reduce the core emittance while stacking, thus reducing the transverse losses and increasing the stack size end point. This new system will also improve the transverse emittance of the antiproton beam transferred to the Main Ring (and thus the transfer efficiency in the Main Ring). Another way to reduce the transverse losses is to increase the transverse aperture of the Accumulator, which can be done by re-doing elements of the vacuum and bakeout system. Before such a massive rework would be contemplated, better understanding of the end point defining parameters must be reached.

Because the stack size end point is determined by the balanace between input flux and loses, a higher stacking rate will also move the end point to larger stacks. At the conclusion of Phase I, the antiproton stacking rate is expected to reach 7×10^{10}/hr vs. the present 1.7×10^{10}/hr. The lower of the two plots in Figure 24 presents the prediction for the shape of the yield vs. stack size for an input flux of 5×10^{10}/hr; it also includes an estimate of the benefit of the new core cooling system by using core emittances twice as small as the present values.

The features illustrated in Figure 24 do not address the problems of beam instabilities that may develop at high intensity. Such instabilities are best addressed as they occur and most likely will be associated with the rf cavities and may require active damping schemes or de-Q'ing of the cavities.

6.3.1 Antiproton Yield

The factors contributing to the antiproton yield which are controllable are the proton spot size and the collection system aperture. The transverse acceptance of the Debuncher ring will be increased from 20π mm-mrad to $\sim 28\pi$ mm-mrad. Along with this improvement, the aperture of the beam line to the Debuncher will be enlarged, and the gradient of the antiproton collecting lithium lens will be increased. Together, these improvements will increase the yield by a factor of 1.5. In addition, another factor of 1.36 should be obtained by a decrease of the proton spot size on the antiproton production target. In order to implement this decreased spot size and in order to utilize higher intensity proton beams a target sweeping system must be developed so that the target is not destroyed. This system is a significant technological challenge.

Debuncher Aperture. The collection system acceptances are defined by the transfer line from the target to the Debuncher, and the Debuncher ring aperture itself. The transverse aperture of the Debuncher is set by the physical dimensions of the pickup and kicker electrodes in the stochastic cooling system. During a study period in September 1987, the Debuncher aperture and the antiproton yield into the Debuncher were measured with these cooling systems removed and it was concluded that the antiproton yield increased by $\sim$ 28% when the tanks were removed. Of course, antiprotons cannot be collected without the Debuncher stochastic cooling systems, but the systems can be rebuilt to open the electrode gaps from 3 cm to 4 cm. This will correspond to a 30π mm-mrad aperture in the cooling tanks; based on measurements in September, a 28% gain in antiproton yield will be realized immediately. The power (number of TWT's) in the Debuncher transverse stochastic cooling system will be doubled which should compensate for the reduced sensitivity due to the electrode modification.

With this accomplished the collection system is limited by the Debuncher injection beam line apertures. Calculations have indicated that further gains can be made if improvements are made to the beam line; the 28% yield increase measured as described above should be able to be increased to 40%. It is planned to replace at least two or more dipoles in the beam line with larger-gap magnets. To fully capitalize on the increased Debuncher aperture, the antiproton collection lithium lens should be operated at 1000 T/m (increased from 800 T/m). Improvements to the mechanical design should allow for reliable operation (one million pulses) at this increased gradient. Additional increases in the antiproton yield (on the order of 10%) could be provided by the use of this higher gradient collection lens. Overall, the improvement factor in antiproton yield could be as high as 50%, if the beam line improvements, Debuncher aperture increase, and higher gradient collection lens, are all implemented.

Targetting. Attempts to increase the antiproton yield at the target favor the use of heavy metal targets, and proton spot sizes as small as possible. With a Debuncher acceptance of 28π mm-mrad, a gain of $\sim$1.25 can be made by reducing the rms spot size from the present 0.3 mm to 0.1 mm. Although the present proton beam spot size is as small as can be achieved with the existing optics, a small radius prefocusing lithium lens, located a few meters upstream from the target, could provide a substantial reduction in the spot size. However, the energy density deposition in the target sets a limit to how far one can go in this direction. Experience in 1985 with the original design target material (a tungsten-rhenium alloy) revealed that the material failed after only a small fraction of its originally expected lifetime. During the 1987 collider run, copper targets were used for most of the run.

Increases in the Main Ring proton intensity will be limited (even for copper) at 2.6×10^{12} protons/pulse for the present proton beam spot size, and will be even more limited if the spot size is reduced using the upstream prefocusing lithium lens. Thus, a method of reducing the energy density deposited by the beam in the target is needed. This can be accomplished by the use of a sweeping system: a fast kicker which sweeps the beam across the target during the duration of the beam spill ($1.6\mu s$). To maintain the advantages in antiproton production of the increased intensity and smaller spot size that this allows, the acceptance of the antiproton collection system must also be swept, requiring another fast kicker downstream from the collection lens.

With the introduction of a sweeping system to reduce the target energy density limitations, it will be possible to reintroduce a heavy metal target, providing an additional gain of 10% in antiproton yield. Thus we expect total yield factor increase of 1.36 from the prefocusing lens, target material, and target sweeping system.

6.3.2 Source Cooling Systems

In addition to the above factors leading to increase in antiproton yield, there are other improvements to the Antiproton Source's cooling systems that are required in order to keep up with increased target cycle rate and proton intensity from the Main Ring or Main Injector.

An decrease in cycle time from 2.6 sec to 1.5 sec is expected as well as an increase in Main Ring-Main Injector intensity per Booster batch from 1.7×10^{12} to $\sim 5 \times 10^{12}$ (see Table 11). Modifications to the antiproton source beam cooling systems are planned in order to keep up with this increased flux. In particular, a Debuncher longitudinal system is planned for the near future that will accommodate the 1.5 sec cycle time associated with "multibatch" production from the Main Ring, and R&D has begun on 4-8 GHz systems for use in the Accumulator core and stacktail systems.

Debuncher Longitudinal Stochastic Cooling. There are several advantages to Debuncher longitudinal cooling. First, there are generally long tails on the momentum distribution in the Debuncher after bunch rotation due to the inherently non-linear nature of the process; beam in these tails is generally lost upon transfer to the Accumulator. The Debuncher momentum cooling will sweep this beam into a Gaussian core, providing an improvement in the transfer efficiency into the Accumulator stacktail. Moreover, the rms width of the distribution presented to the stacktail will be reduced; consequently, the stacktail gain could be reduced, which will reduce the betatron heating of the core by the stacktail. This will be particularly important in rapid cycle operation with "multibatch" targetting, when the stacktail gain must be increased to cope with the higher flux. Finally, the requirements on

	Protons per MR/MI Cycle	Cycle time (seconds)	MR/MI Power(MW)	Proton rate (10^{12}/s)	Factor
Now	1.7	2.6	7	0.65	
MR – 3 batches (1.5 s cooling)	1.7×3	6 (3.25 flat) (eff 2 sec)	9	0.85	1.3
Linac/MR 3 batches	2.8×3	"	"	1.4	$1.7 \times 1.3 = 2.2$
Linac/MI	4.2–5	1.5	6	2.8–3.3	$2.5 \times 1.7 = 4.3 - 5$

Table 11: Steps for increasing Main Ring — Main Injector intensity and repetition rate.

the bunch narrowing process in the Main Ring prior to extraction for antiproton production will be less severe, because the momentum cooling can compensate for some inadequacies in the bunch rotation. This will be important because the bunch narrowing process suffers inevitably in the "multibatch" Main Ring operation. Debuncher momentum cooling will make the Antiproton Source less sensitive to the proton longitudinal emittance and bunch shape at 120 GeV.

The Debuncher momentum cooling system will be a high-power system, with typically 1600 watts of power (mostly thermal) and 256 pickups and kickers. A high performance notch filter will also be required. The system bandwidth will be 2-4 GHz.

Accumulator Core Cooling System. The Accumulator core has been chosen as the first place to implement a 4-8 GHz cooling system for two reasons. First, it is a relatively inexpensive, low-power system that can be implemented rapidly. Second, it will provide immediate benefit in two ways:

- During antiproton stacking, it will help to counteract the increased stacktail heating of the core that will result from the higher stacktail gain needed for the more rapid cycle rate associated with "multibatch" operation, and
- the antiproton emittance in the core will be reduced so that smaller beams can be sent back to the Main Ring and Tevatron for collider operation. In general, this will make the antiproton transfer efficiency better.

Accumulator Stacktail System. The need for improvements in the stacktail system is under evaluation. The present system has demonstrated the ability to stack at rates of 3×10^{10}/hr (with protons) and has been designed for rates of 10^{11}/hr. Other factors however enter in to determine what improvements will be required as the repetition rate increases. The system gain will need to be increased with the 1.5 sec cycle rate. Unfortunately this will increase the betatron heating of the core that in turn may determine the limiting stack size. In addition, beam loss from the stacktail will also contribue to the limiting stack size, and system instabilities may limit the cooling system gain. Understanding these trade-offs and the benefits of higher frequency for the expensive stacktail system is presently underway.

In conclusion, it is appropriate to mention that though the stack size limitation does not appear to be an insurmountable problem at this time, the saturation of the stacking rate as the stack grows does work against gains that are realized by proton flux improvements (linac and Main Injector). If the stack size limit should indeed turn out to be in some sense fundamental, then we would review ideas such as refilling only a fraction of the antiproton bunches in the Tevatron whenever the source becomes saturated. Such a scheme might be particularly attractive if bunched beam cooling in the Tevatron could be accomplished.

6.4 The 400-MeV Linac and Other Intensity Improvements

Table 11 lists the steps for improving intensity and repetition rate from the Main Ring or Main Injector for antiproton production. Intensity increases in MR/MI can also be projected as fixed target Tevatron intensity increases by multiplying batch intensities by 12.

The first step in proton flux improvements for antiproton production comes from trying the "multibatch" targeting operation. This mode calls for injecting and accelerating three booster batches in the Main Ring. (The Main Ring is 13 times the circumference of the Booster or Antiproton Source, but present production calls for utilizing only one batch. This lack of utilization of the full capability of the Main Ring in antiproton production has been one of the frustrations of the present operation.) Once on flattop the batches are extracted sequentially to the production target. The time between targetting cycles is then limited by the capability of the antiproton beam cooling systems. Developments to be undertaken shortly should allow a reduction of this time to 1.5 sec (on flattop) for an effective average cycle time of 2 sec.

One of the potential problems with multibatch operation that may make it turn out to be unfeasible is that the targetting procedure calls for a bunch shortening operation of the beam in the Main Ring prior to extraction. (The short duration rf bunches are required in order to minimize the longitudinal emittance required in the Debuncher for the wide momentum spread secondaries.) To be successful with three batch operation the bunch shortening must be performed adiabatically three successive times without appreciable emittance dilution. More effort and studies need to be expended in order to determine the feasibility of this approach. (And, as discussed earlier, Debuncher longitudinal cooling will help.) If successful this mode will increase the antiproton stacking rate by a factor of 1.3

The linac upgrade calls for increasing the energy of the linac from 200 MeV to 400 MeV. As will be discussed below, this should yield in a direct way a factor of 1.7 in intensity from the Main Ring for both the antiproton production and the fixed target Tevatron operation. In addition, smaller emittance proton bunches at the same intensity as is presently obtained for collider operation should be possible, thus increasing the luminosity ($\mathcal{L} \propto N/\epsilon$). Taking these two improvements together, the linac upgrade should provide an increase in integrated luminosity of about a factor of 2, even with consideration given for saturation of the antiproton stack.

The final proton flux improvement comes from the Main Injector. (See Section 5.) Intensities from the Main Injector of 5×10^{12} protons per Booster batch are conceivable, though beam instability problems will undoubtedly need to be addressed throughout the Accelerator chain. More conservatively, bunch intensities for fixed target and antiproton production 2 1/2 times the present can be expected. Wwith a cycle rate of 1.5 sec, proton fluxes $4\frac{1}{3}$ times the present could be achieved for antiproton production.

6.4.1 Benefits of The Linac upgrade and The Main Injector

The expected performance of the accelerator chain with the linac and Main Injector upgrades is best illustrated in Figure 25. The present measured normalized emittance from the Booster as a function of bunch intensity is plotted. As can be seen at low intensities the emittance is just that obtained from the linac and Booster injection transport line. Above a certain intensity the emittance grows linearly and the slope can be associated with a beam space-charge tune spread of $\Delta\nu = 0.37$ or a large fraction of the available tune space (0.5). Presently the beam emittance blows up at injection time until the tune spread is small enough to allow for stable particle orbits.

The physical mechanism is as follows; A proton located within a bunch in the Booster is subject to both electric and magnetic forces due to other protons within the same bunch. Since these forces depend on the transverse position of the proton, they provide additional focusing which changes the tune of a particle in a manner which depends on its oscillation amplitude. As a result an incoherent tune spread is introduced in the beam whose magnitude is given by

$$\Delta\nu_{s.c.} = \frac{3r_p N_t}{2B\beta\gamma^2\epsilon_N}$$

where r_p is the classical radius of the proton, N_t is the total number of particles in the accelerator, B is the ratio of average to peak current, β and γ are the usual kinematic factors, and ϵ_N is the normalized (95%) transverse emittance. The kinematic dependence on β and γ arises because the electric and magnetic field contributions exactly cancel as β approaches unity. The strong kinematic dependence insures that in any accelerator complex the total tune spread within the beam is apt to be largest at injection into the lowest energy ring. By increasing the linac energy from 200 MeV to 400 MeV we increase the kinematic factor, $\beta\gamma^2$ from 0.83 to 1.45. This will raise the fundamental limitation on the Booster phase-space density by about 75%. The improvement is illustrated by the second slope on Figure 25. Also shown is the increased normalized aperture limit resulting from injecting into the same physical aperture with a higher energy beam.

Other potential benefits of the high energy injection are:

1. Better field quality at Booster injection. This will come about for two reasons. First, the higher injection fields will reduce the effects of remanent fields in the Booster magnets, and second, the smaller beam size out of the linac will result in the beam being spread over a region of more uniform field than it is at present. It is hard to quantify the expected benefit from this effect.

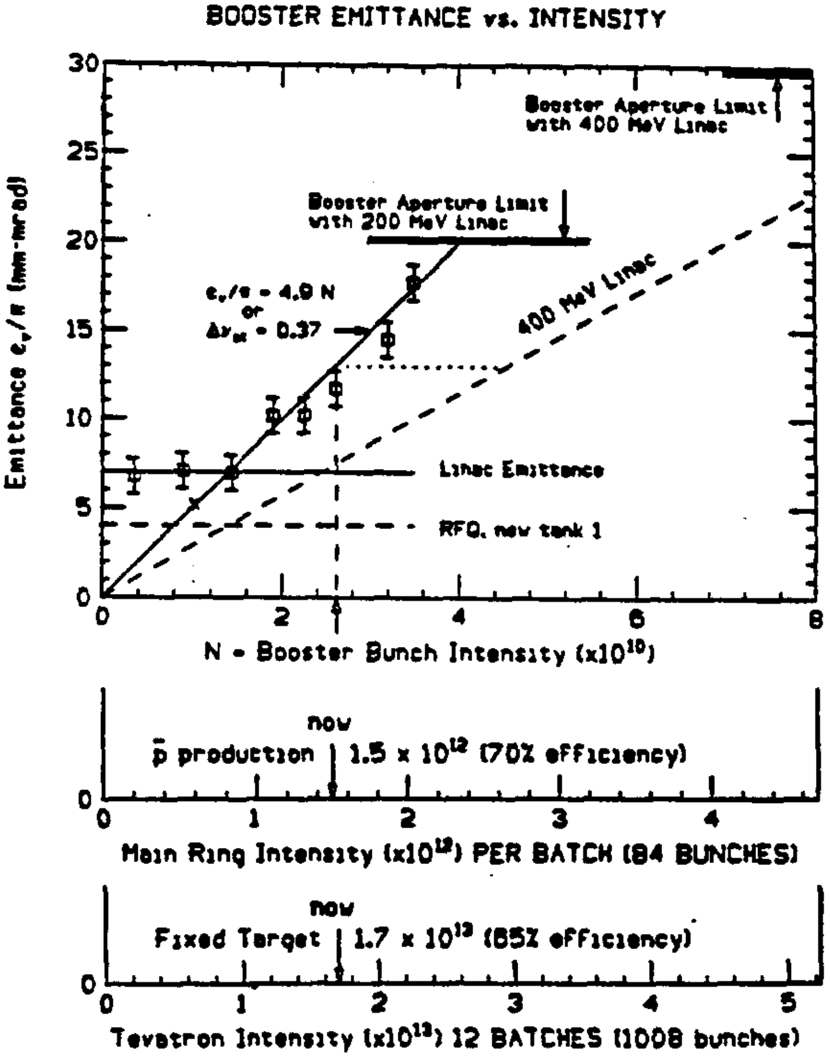

Figure 25: Booster emittance as a function of beam intensity. The bottom two axes reflect the intensities produced by the Main Ring (single batch, such as used during antiproton production), and the present Tevatron (1000 bunches, fixed target operation).

2. Improved RF capture. The higher injection energy will result in a larger bucket area during the initial stages of acceleration as well as reducing the frequency swing during the acceleration cycle by about one-third. Conversely it may be possible to remove some of the RF cavities from the Booster to lower the impedance presented to the beam. This may be a very important requirement to control instabilities as intensities increase.

Refering to Figure 25, one can trace the expected intensity improvements from the linac and the Main Injector. Present operation is indicated by the arrow at bunch intensities of 2.6×10^{10} and emittances of 13π mm-mr, about the acceptance of the Main Ring for short dwell times. This operating point should move to $\sim 4.6 \times 10^{10}$ and 13π with the 400 MeV linac. Then with replacement of the Main Ring with the Main Injector larger acceptance should be possible and the operating point should move up the new "load line" to emittances of at least $20\pi - 25\pi$, corresponding to intensities of $7 - 8 \times 10^{10}$/bunch. Referring to the other intensity scales this should be equivalent to $4 - 5 \times 10^{12}$/Booster batch from the Main Injector and about $4.5 - 5 \times 10^{13}$ into the Tevatron for Fixed Target. Needless to say, such intensities will require careful consideration of beam instability and quench problems.

6.4.2 The 400 MeV Linac and Low Energy Upgrade

The linac upgrade consists of replacing the downstream half of the present 200 MHz drift tube linac with a higher gradient side coupled cavity structure driven by a seven module 800 MHz, 12 MW/unit klystron power system. Effective accelerating fields are 6 MeV/m ($ET \cos\phi$) with maximum surface fields of 40 MV/m.

Substantial R&D effort is underway with the building of two prototype power cavity sections, the procurement of a prototype klystron, and development of modulator systems.

Additional effort is being directed toward the improvement of the low energy end of the linac with the conceptual design of an RFQ for injection at 2 MeV (instead of 3/4 MeV) into a new first drift tube tank. This new low energy improvement should provide lower emittance linac beams to the Booster, which may be of value for Collider luminosity by improving the bunch emittance (see Figure 25). It will also replace the cumbersome Cockcroft-Walton preaccelerator with the much more compact and modern RFQ system.

6.5 1 TeV in the Tevatron

Present operation of the Tevatron is at 900 GeV for collider and 800 GeV for fixed target. These operating points are based on experience and a conservative approach to operating margin for spontaneous quenches in collider mode and extraction beam loss induced quenches in fixed target mode. The entire ring was ramped to 925 GeV excitation without quench at the beginning of the ongoing collider run. We believe this is close to the limit achieveable at present operating temperatures. Data from the Fermilab Magnet Test Facility prior to installation of the magnets gave an average quench limit of about 1 TeV with a standard deviation of about 50 GeV. Thus, though a few magnets with low quench characteristics have been replaced, we believe that a general program of more magnet replacement would not be economically feasible because we are already well beyond the tail of the quench distribution. Lower temperature operation is however possible, and an R&D effort is underway to determine just what the specific practical problems are.

The program which is being pursued is one of installing "cold compressors" in series with the 2-phase flow returning from the magnet strings to the 24 satellite refrigerators. These compressors should lower the return pressure from 1.3 atm to 0.7 atm and gain about 0.6 K, which should be sufficient for 1 TeV collider operation. In order to operate at subatmospheric pressure the 2-phase side of the magnet system must be made leak tight or contamination will become a reliability problem. Should this indeed be the case, substantial gains to above 950 GeV are probably possible without going below atmospheric pressure.

Two types of cold compressors are under evaluation; a reciprocating type and a turbine type. At the present time the reciprocating type appears to be the most practical as the turbine can be destroyed if any 2-phase liquid strikes the rotating blades. It is hoped to have a one sector test of the system in the summer of 1989 prior to the shutdown.

Temperatures lower than $\sim$ 3.8 K for the whole Tevatron system are not considered viable at this point. This is because of the large static heat leak of the magnets, the additional heat load that the components that lower the temperature introduce, and the additional relative refrigeration load at 4.2 K that heat leak at the lower temperature requires. (It is estimated that every watt at 2 K requires 7 watts at 4.2 K.) Without major modification, the capacity of the satellite refrigerators is limited to $\sim$1000 watts and the present static heat load is $\sim$600 watts, $\sim$200 watts is needed for operating safety margin.

Fixed target operation above 800 GeV will also be possible. A test run at higher energy is needed to evaluate just what energy is practical for the present operating temperature, and what might be achieveable after the cold compressor installation. Three factors enter: a) temperature margin needed for beam loss (slow spill extraction only); b) reliability of the magnets under ramping conditions, (forces on magnet coils and leads go as I^2, thus stress at 900 GeV is 25% above the present 800 GeV level); and c) refrigerator capacity — fixed target operation is at $\sim$800 watt per refrigerator. The cold compressors will introduce an additional heat load and it may be necessary to make trade-offs between ramp rate and energy.

6.6 Benefits

- Provision for a second low -β interaction region (D0) and a redesign of the B) interaction region so that the two IR's can be operated independently to β^* as low as $\frac{1}{4}$ m.

- Provision for separated orbits to reduce the beam-beam tune shift so that the luminosity can be increased.

- Increased antiproton yield per proton by a factor of two.

- Increased antiproton cooling system capability for 1.5 second repetition rate and increased intensity.

- Increased proton repetition rate for antiproton production by a factor of 1.3 with "multibatch" operation.
- Increased proton intensities by a factor of 1.7 from the 400 MeV linac upgrade.
- Increased Tevatron collider operating energy to 1 TeV.
- Potential intensity for fixed target operation about 3×10^{13} protons per pulse.
- Potential luminosity for collider operation 1×10^{31} at 1 TeV.

7 Costs and Schedules

The costs presented in this section are entirely for the 400 MeV Linac, The Main Injector, and the New Tevatron. They do not include the smaller costs for the low beta insertion for D0 which will be installed in the existing Tevatron in 1990, for the addition of primary proton beam transport to bring a 120 GeV proton beam to the Neutrino experimental area, or for the cost of upgrading the secondary beam line to the P-East experimental area from 250 GeV to 500 GeV which will be done in 1989. These costs have traditionally been funded from a mixture of Accelerator R&D funds and AIP funds or a mixture of experimental area R&D funds and capital equipment funds depending on the details of the project. It is envisioned that the Upgrade will be paid for by a combination of incremental funds and funds out of the base Laboratory budget which traditionally go to investment in future facilities. The breakout is given in Table 18. *Clearly, the Upgrade must not be allowed to thwart the vigor of ongoing physics which it is designed to amplify.* The costs given in Table 18 do not include the funds for upgrading the CDF and D0 collider detectors, building a new specialized detector for bottom physics, or upgrading any of the fixed-target multiparticle spectrometers. Traditionally the cost of detector upgrades and new detectors have been paid with equipment funds, and the development of new detector elements have been paid for with R&D funds that have been part of Fermilab's annual base budget through the years. After close scrutiny by the Laboratory, approval is given for modifications to existing beamlines, spectrometers, and collider detectors that fit within the envelope of the annual base budget. It is possible to keep the costs for these changes within the framework of the annual budget, since time, as well as money, is a variable of choice. Since there are costs for these items the assumption about the annual budget are given here in Table 12 and in the text associated with Table 18.

It should be noted that these figures are equal to Fermilab's FY90 request to DOE made in FY88. They are higher than the actual budget for FY89 by 15%. This budget will allow between 9 and 11 months of operation during each fiscal year, depending on the details of the work that is planned for each transition between Collider and Fixed-Target operation.

The costs in this section have been derived in \$FY89 and then inflated in accordance with DOE guidelines so that the total project costs are expressed in then year dollars. In order to do this a funding profile and hence a schedule are needed. The proposed schedule assumes

Table 12: Breakdown of the Annual Base Budget for Fermilab in FY90 M\$ *

Facilities Operations & Research	145.9
R&D	22.3
Accelerator Improvement Fund (AIP & GPP)	17.0
Capital Equipment	37.0
Total Annual Base Budget	222.2

* 1989 WPAS Laboratory Budget Request (Plant funds deleted)

that Phase I is completed during FY89, 90 and 91. More specifically the construction for the linac energy increase will take place in FY90 & FY91. The second phase, The Main Injector, receives initial construction funds in FY91 and follows a relatively flat spending profile through FY94, with a small amount of money needed in FY95. An accelerator shutdown of 9-11 months duration starting in the Spring of '94 is required, during which time both the Main Injector connection to the Main Accelerator tunnel and the installation of the New Tevatron take place. A significant amount of installation work in the Main Injector will have occurred prior to this shutdown. The schedule for superconducting magnet fabrication follows directly from the need to complete production by the end of '94. This is envisaged as a 36 month production run of ~16 dipoles per month, significantly less than the peak Tevatron production rate of 40 per month, which flattens the spending profile and manpower demands. With a start of magnet preproduction in FY91, the full production rate is attained at the beginning of FY92 and continues through the end of 1994.

The estimated costs of the first two phases of the project are bottoms-up estimates derived in the case of the linac and the Main Injector from a WBS structure. The smaller AIP projects do not have a WBS breakdown. The estimate for the superconducting ring is based primarily on a design concept developed during the 1988 Snowmass workshop.

7.1 Phase I

The largest single item in Phase I is the linac energy upgrade from 200 to 400 Mev, and the itemized sub- system costs shown in Table 13 are derived from the WBS structure. The major components are the accelerating structures with their associated RF drive equipment. The escalation is consistent with the proposed two year (FY90 & 91) funding profile.

Several of the other items included under Phase I are in progress, such as the improvements to the interaction region optics, the electrostatic separators, and a number of the other initial steps in this phase. Other aspects of Phase I will commence in FY90 and FY91. These activities are supported by AIP and R&D funds as shown in Table 14 and Table 15.

7.2 The Main Injector

The Main Injector cost estimate summarized in Table 16 is separated into three sections: the injector ring, the beamlines and the civil construction. The synchrotron will use quadrupoles, the RF system, and the correction elements (other than sextupoles) from the Main Ring. The remaining components will be new. New dipole construction is the bulk of the magnet costs. The rapid cycling nature of the Main Injector needs a large power distribution network. Accelerator sub-systems and controls are all new components.

New dipole magnets will be installed in the Main Injector enclosure as they become available, before the decommissioning of the Main Ring. Once the Main Ring is shutdown then the quadrupoles and other elements will be transferred over so that commissioning of the new ring can start before the completion of the work in the Main Accelerator enclosure. The civil construction in the F0 region and the beamlines are sufficiently far away from the Main Injector to allow this.

Table 13: Linac Energy Increase 200 → 400 Mev

Description	Cost (FY89 $K)	
Accelerator Cavity systems	5533	
RF Power supplies	5246	
Transition section	917	
400 Mev diagnostics	110	
Booster transfer line	380	
Debuncher	594	
Booster injection	229	
Building modifications	1630	
Total unit cost (FY89 $K)	14639	
EDIA (16%)	2342	
G/A (0.7%)	119	
Contingency (20%)	3420	
Escalation (7.2%)@	1480	
Total Project TEC ($K then year)		22000
Total R&D*@	4933	
Pre-operating*	690	
Capital equipment	350	
Total project cost TPC ($K then Year)		27973

* Includes G/A
@ Assumes FY90 & 91 construction funding

Table 14: Accelerator Division AIP Projects FY89-91 $K

Description	FY89 (budget)	FY90 (revised 1/89)	FY91 (requested)
Electrostatic Separators	2350		
Cold Cryogenics	1500		
Debuncher cooling	800		
B0 Low Beta Improvements		2500	
Tevatron colliding abort		1500	
Separated orbit corrections		300	
Debuncher cooling		800	
Preaccelerator upgrade		1250	
Target sweeping system			500
Tevatron kickers			350
Accumulator stacktail cooling			1500
Linac Tank #1 upgrade			1300
Other AIP projects		2000	3650
Total AIP projects	4650	8350	7300

Table 15: Accelerator Division R&D Projects FY89-90 $K

Description	FY89 (budget)	FY90 (90 WPAS)
Linac upgrade - high energy (Phase I)	1507	
Linac upgrade - ion source (Phase I)	100	
Electrostatic separators (Phase I)	500	
Low Beta quadrupoles (Phase I)	900	
High field magnets (Phase III)	900	
Cold compressors (Phase I)	250	
Accumulator 4-8 GHz cooling (Phase I)	200	
Lens sweeping system (Phase I)	100	
FY89 G&A (33%)	1438	
Main Injector magnets (Phase II)		1000
Linac upgrade - high energy (Phase I)		1185
Linac upgrade - ion source (Phase I)		726
Cold compressors (Phase I)		375
Magnetic refrigeration (Phase III)		346
Pbar cooling systems (Phase I)		1095
High field magnets (Phase III)		4323
Other R& D		443
FY90 G&A (34%)		3345
Total R&D projects	5794	12837

Table 16: The Main Injector Cost Estimate

Description	Cost (FY89 $K)	
Main Injector Ring		33610
Magnets	18163	
Vacuum	366	
Power Supplies	3992	
RF systems	186	
Abort & Extraction	88	
Instrumentation & Controls	1405	
Utilities, Safety, Install	9406	
Beamlines		15055
Magnets	5318	
Vacuum	294	
Power Supplies	2458	
Injection & Extraction	954	
Instrumentation & Controls	1189	
Utilities, Safety, Install	4841	
Conventional Construction		31000
Site preparation	4000	
Tunnel and service buildings	19500	
F0 enclosure and building	4700	
Primary power distribution	1600	
Paving and Landscaping	1200	
Total unit cost (FY89 $K)		79665
EDIA (15%)		11950
Contingency (20%)		18320
G/A (0.7%)		770
Escalation (20%)		21480
Total project TEC ($K then year)		132200
R & D (includes G&A)		9100
Pre-operating (includes G&A)		2000
Capital Equipment		910
Total Project Cost ($K then year)		144200

The beamlines connecting to the Booster, Antiproton Source, the Tevatron, and the Switchyard, represent a significant fraction of the total project. The beamlines incorporate ~100 B2 dipoles reused from the Main Ring but do require the fabrication of a significant number of quadrupoles. There is also ~2000m of new tunnel associated with the beamlines.

The major item in the civil construction is the subsurface enclosure for the beamlines and the injector ring. Other items include the service buildings, primary power distribution, cooling ponds, and roads.

The R&D costs will provide for the prototyping and testing of critical new components. The major elements of the R&D phase will be the high current dipoles and associated power supplies, together with the special length quadrupoles. The pre-operating costs are estimated to cover a period of commissioning of six months duration. The capital equipment funds cover test instruments, electronics, and other general equipment to support the project.

Modifications to the existing Switchyard and external beams to accomodate the 120 GeV high intensity physics beam to the Neutrino area as well as low intensity test beams to all the fixed target experimental areas have been estimated to cost $2400K. The bulk of this money goes toward the quadrupoles and power supplies in the high intensity line. This part of the project will be supported by AIP funds, and will be implemented prior to the completion of the Main Injector for use with the Main Ring.

7.3 The New Tevatron

The costs as derived in this section have been presented as a construction project to provide consistency with the earlier projects. Since no civil construction is actually involved it may not be necessary to fund the project in this fashion.

The costs of the new superconducting ring are dominated by the superconducting magnet components. The unit cost of a 8.5m, 8.0T dipole is estimated to be $130.5K and 580 of these are needed. The standard lattice quadrupoles and the straight section and low-beta special quadrupoles are $38.5K and $120.0K respectively, with 180 of the former and 38 of the latter required. The other magnetic elements are the spool piece correction magnet package which contains higher order elements as well as dipoles and quadrupoles. We need 204 of these devices which are estimated at $65.7K each. These estimates are based on the quadrupoles and spool pieces currently under construction for the new Tevatron interaction region, the SSC cryostat costs, and collared coil assemblies for replacement Tevatron dipoles.

The existing Tevatron cryogenic system with the Central Helium Liquifier complex and the 24 satellite refrigerators will be used essentially as is. The lower heat leak from the cold iron magnets results in a smaller cryogenic load than at present. New elements for the cryogenic system are feedcans, bypass regions, a quench relief system, and instrumentation and controls. In order to lower the temperature to 1.8 K a new stage must be added to the satellite refrigerators to allow lower pressure operation or alternatively a magnetic refrigerator. The new cryogenic elements are $7.3M and the lower temperature implementation is estimated to be ~$10M.

The Tevatron main power supplies will operate in ramping mode to 5.5 KA (1.5 TeV) but 3 new holding supplies are needed to accomodate the higher flattop excitation for both

Table 17: The New Tevatron Cost Estimate - FY89 ($K)

Description	Cost	
Magnets (5/6)		83819
Dipoles	75690	
Arc quads	6930	
Special quads	4560	
Correction Elements	13403	
Power Supplies		1890
Holding supplies	1050	
Energy Dumps	840	
Correction elements	0	
Cryogenic system (5/6)		14084
Bypasses, reliefs, valves	7300	
Low temperature	9600	
Sub-systems		2130
RF	0	
Instrumentation	0	
Utilities	0	
Injection	0	
Beam abort	450	
Resonant extraction	380	
Controls	0	
Vacuum	0	
Magnet stands	500	
Install, hook-up, and survey	800	
Total Unit cost (FY89 $K)		101923
EDIA (16%)		16308
Contingency (25%)		29558
Escalation (19.5%)		28819
Total project TEC ($K then year)		176608
Total R&D		49000
Pre-operations		2000
Capital equipment		750
Total project costs (then year $K)		228358

fixed target and collider operation. These supplies are similar to the Main Injector supplies and cost $350K each. The energy extraction system will need new dumps (12) capable of higher power dissipation than at present, estimated at $70K each. The correction element power supply system can be designed to use the existing equipment.

Of the other major sub-systems needed for a complete accelerator many components can be used from the present Tevatron. The RF system will require no change. Beam instrumentation such as intensity and emittance monitors, beam position electronics and loss monitors, Schottky pick-ups, and electrostatic deflectors, will all be reused from the Tevatron. The injection energy remains at 150 GeV so that magnetic septa and fast risetime kicker magnets will work in either accelerator. The collider mode beam abort system with the addition of a resonant pulse charging supply will operate at the higher energy as will the present abort logic hardware. The fixed target abort system which relies on an external abort channel will require an additional 3 magnets to increase the energy of this channel. The resonant extraction system needs 3 more magnets in the extraction channel and one additional electrostatic septum module; the feedback system and spill control quadrupoles will require no modifications. Vacuum equipment in the warm regions such as ion pumps, ion gauges, and beam valves is all reusable.

Systems tests will be performed with 1/6 of the new Tevatron (4 cryoloops). Four houses worth of components will be fabricated on R & D and installed for complete systems tests. Past experience has indicated that such total system tests are invaluable in achieving successful and efficient final installation and commissioning. Also included in this category is tooling for the magnet production together with 20 preproduction dipole prototypes. The pre-operations is estimated to cover a six month period of cooldown and commissioning.

Costs associated with upgrading the Switchyard and the external beam lines to handle the increased energy have been estimated at $5100K. Increasing the energy of the external beams involves upgrading the major bend points and the beam splitting areas. The major bend points presently use non-accelerator quality superconducting dipoles running at lower excitation than the magnets in the ring. Replacing these magnets with higher quality Tevatron dipoles from the present ring incurs no cost overhead. These magnets would be required to operate at 4500A; about one half of the accelerator magnets meet or exceed this requirement. The external beams major bends need 138 of these dipoles and 45 quadrupoles. A small number (6) of high field dipoles (6.6T) are also needed. The beam splitting stations will need new magnet septa (31) and some new electrostatic septa (11) to augment the existing devices. A small amount, 120 feet, of new tunnel enclosure is necessary. Increasing the energy of the external beam-lines is assumed to take place as an AIP project.

7.4 Funding Profile: Incremental Needs (All costs included)

The funding profile is derived from the schedule given at the beginning of this section viz. Phase I complete during FY91, Phase II & Phase III completed in 1995. The amounts are in then year $K, and are incremental on the Laboratory FY90 Budget.

Table 18: Overall Budget Presentation

Incremental (Plant):

Phase I	**FY90**	**FY91**	**FY92**	**FY93**	**FY94**	**FY95**	**Total**
Linac 400 MeV	13000	9000	0	0	0	0	22.0 M
Phase II							
Main Injector	0	30000	34000	34000	32000	2200	132.2 M
Phase III							
New Tevatron	0	0	57700	51500	39800	28300	177.3 M
Incremental Total:	**13000**	**39000**	**91700**	**85500**	**71800**	**30500**	**331.5 M**
Base Funding Contributions (R&D, AIP, etc.):	17800	22900	13900	14300	15400	4000	88.3 M

7.5 Detector Costs Estimate

It is known that the Collider Detectors must be upgraded. Although firm cost estimates have not been made, *guestimates* are provided below:

Table 19: Detector Upgrades

CDF (for operation at 4×10^{31})	\$25 Million
D0 (for operation at 4×10^{31})	\$15 Million
BCD (Possible new collider detector for B physics, not yet approved)	\$40 Million
TOTAL:	\$80 Million

If an equipment budget of \$30 million per year over the period 1990-95 is assumed, this results in \$180 million. Of this some \$20 million goes to miscellany of computers, peripherals, cars, etc. This leaves \$80 million for fixed target and beam lines over the six year period. This is tight and implies fewer (but hopefully more incisive) fixed target experiments. Within the flexibility of the numbers and the time scales, one and perhaps two fairly massive new fixed target initiatives can be accomodated.